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WAVELENGTH DEPENDENCE OF SEA ECHO

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ABSTRACT

A review of the literature on sea echo measurements has been made for frequencies from a few tens of megacycles to a few tens of gigacycles. Effects of changes in wavelength, angle of incidence, polarization, and sea condition on σ^{O}, radar cross section per unit area of the sea, are discussed. For microwave frequencies, the range of possible grazing angles can be divided into three fairly distinct regions: "near grazing incidence," the "plateau region," and "near vertical incidence." Within each of these regions, the dependence of σ^{O} on grazing angle, and the dependence of σ^{O} on wavelength can be characterized to some extent. However, the boundaries of the three regions change with wavelength, sea surface condition, and polarization.

In the near grazing incidence region, σ^{O} increases rapidly with increases in grazing angle and with decreases in transmitted wavelength. For the plateau region, σ^{O} increases very slowly with increases in grazing angle and with decreases in transmitted wavelength; it appears that σ^{O} for transmitting and receiving horizontal polarization is more dependent on wavelength than σ^{O} for transmitting and receiving vertical polarization. The magnitude of σ^{O} increases for increases in sea roughness for small grazing angles and for the plateau region. For near vertical incidence, σ^{O} tends to decrease for increases in sea roughness and the dependence of σ^{O} on wavelength appears to be weak. The available data for frequencies below the microwave region are so meager that no overall conclusions could be drawn. However, the data do not disagree with the trends indicated by the microwave data.

Measurements now being made by personnel of the Naval Research Laboratory and of the Johns Hopkins Applied Physics Laboratory are briefly described, and recommendations are made concerning efforts to obtain more information on sea echo.

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I. GENERAL BACKGROUND

A. Introduction

A knowledge of the magnitude of sea echo for different wavelengths and various states of the sea is of great importance to the radar system designer and the theoretician who wishes to better understand the scattering mechanisms of the sea. The determination of wavelength dependence is exceedingly difficult because the scattering cross section is dependent on many uncontrollable environmental factors and a measurement usually requires the absolute calibration of at least two radar systems; then there are at least two sets of system errors involved.

During the early days of radar, data [Kerr, 1951, pp. 481-587; Goldstein, 1946; Davies and Macfarlane, 1946]* on wavelength dependence were not inconsiderable, and even then there was little doubt that, within the microwave region, the smaller the wavelength the larger the value of echo strength for any given grazing angle and for a given sea state. More recently, Katzin [1957] reported that measurements he had reviewed indicated a wavelength dependence close to λ^{-1}; Wiltse, Schlesinger, and Johnson [1957] obtained data for horizontal, vertical, and circular polarizations, and they found no significant correlation of σ^{0} with wavelength; Grant and Yaplee [1957] obtained data for transmitting and receiving vertical polarization, and their data seem to indicate a λ^{-1} dependence for grazing angles of about 10° to 45°. Although diverse opinions are expressed even in the more recent literature, the results seem to indicate that the dependence of σ^{0} on wavelength is between λ^{0} and λ^{-1} for all incidence angles except those near grazing and near vertical incidence.

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* References are listed at the end of the report.

The problem is complicated by the fact that σ^{o} depends on transmitted and received polarizations. It is generally recognized [Kerr, 1951; Boring, et al., 1957; Macdonald, 1956] that for calm seas the average cross section for transmitting and receiving vertical polarization (σ^{o}_{VV}) exceeds that for transmitting and receiving horizontal polarization (σ^{o}_{HH}). The difference decreases as the sea becomes rougher, and it has been observed [Kerr, 1951; Boring, et al., 1957; Katz and Spetner, 1960] that σ^{o}_{HH} sometimes exceeds σ^{o}_{VV} by a few decibels.

Sea echo or sea return is caused by the various scattering mechanisms within the resolution cell of a radar. Goldstein introduced the quantity σ^{o}, radar cross section per unit area of sea surface, to provide a normalized parameter which could be used to describe radar cross section of the sea. Using the definition of σ^{o}, the radar cross section σ equals σ^{o} A, where A is the physical area of the sea surface contained within the radar's cell of resolution. Details regarding the definition of σ^{o} are contained in Kerr [1951, p. 481] and Skolnik [1962, p. 527]. In using the quantity σ^{o} to describe radar echo, it is tacitly assumed that the echo is caused by a large number of scattering mechanisms that are distributed uniformly throughout the physical area illuminated by the radar.

The radar cross section per unit area, σ^{o}, has been found to depend on the grazing angle θ (see Figure 2), the transmitter wavelength, λ, and the polarizations of the incident and reflected waves. Sea echo has been found to be sensitive to wind speed, wind direction, wave height, and wave direction. For example, an increase of 10 db in σ^{o} in a one-minute period has been observed at the same time as a sudden increase in wind speed. From the above, one should not be surprised to find that reported values of σ^{o} differed by many decibels even when great care was exercised in measuring radar parameters and sea conditions.

B. Dependence on Angle of Arrival

Experience has shown that the dependence of σ^{o} on grazing angle is of the general form shown in Figure 1. There are three general domains of variation of σ^{o} as a function of θ, and the magnitude of the variation of σ^{o} in these domains is a function of polarization and environmental conditions. The case of small grazing angles was studied extensively during World War II [Kerr, 1951; Davies and Macfarlane, 1946]. Beckmann and Spizzichino [1963] have provided a comprehensive review of the small grazing angle and high grazing angle domains. Other comprehensive references on sea echo include Wolff [1960] and Katzin, Wolff, and Katzin [1960].

1. Near Grazing Incidence

The rapid change of slope of the $10 \log_{10} \sigma^{o}$ versus $\log \theta$ curves in the vicinity of the "critical angle" (θ_c in Figure 1) has been explained by Katzin [Povejsil et al., 1961] on the basis of the interference pattern formed by the difference of path length between the direct ray to the scattering element and the ray reflected from the surface of the sea (see Figure 2). As the grazing angle increases, the increase in ΔR, the path-length difference, decreases the spacing between the nodes and antinodes of the interference pattern (for some examples, see Figure 3). At small depression angles, the scattering elements extend only a short distance into the first antinode. As this angle increases, the interference pattern scales downward so that the scattering elements penetrate more deeply into the first antinode. The critical angle is approached as the first antinode encompasses substantially all the scattering elements. Thus the critical angle decreases

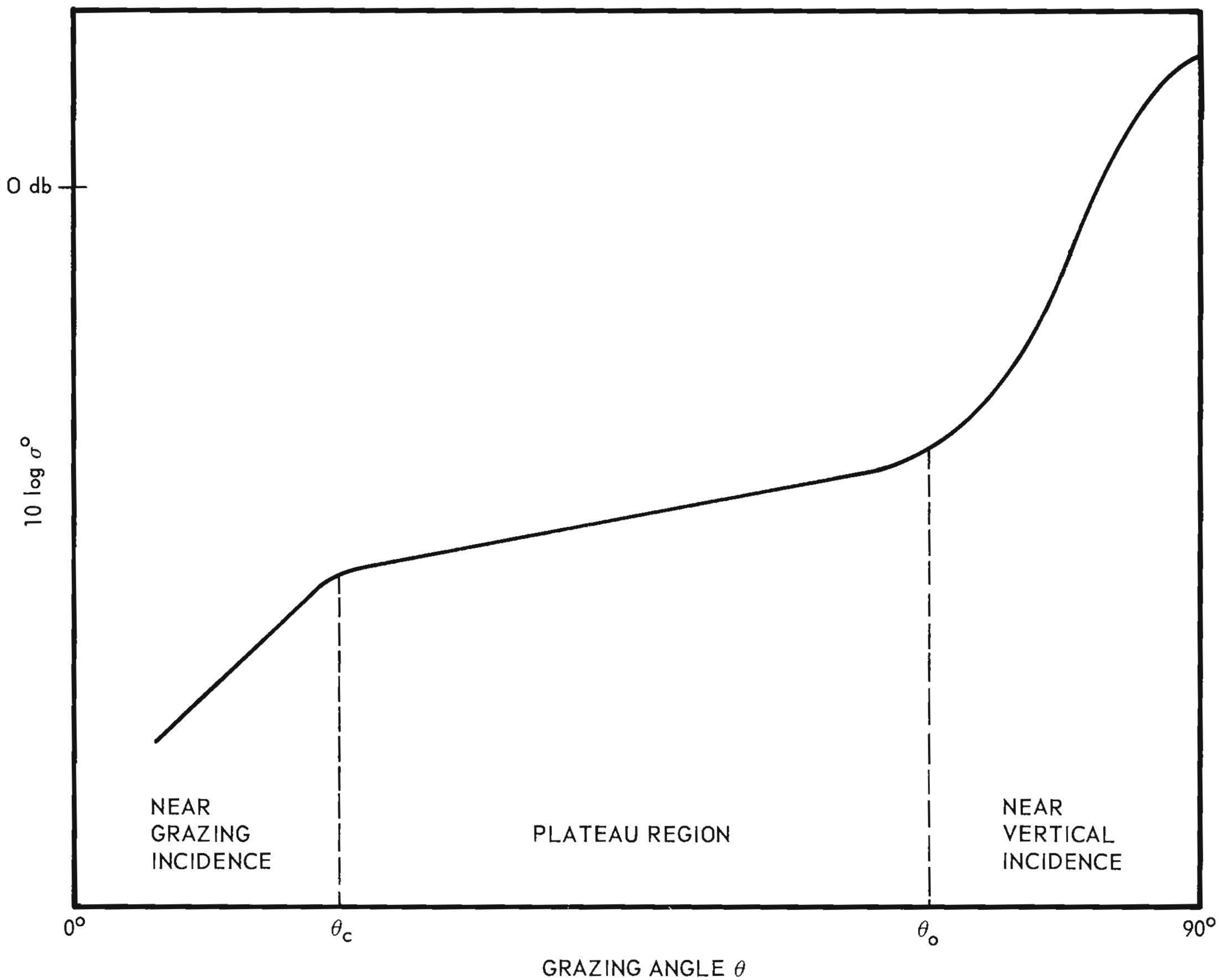

Figure 1. General Shape of the Dependence of σ^{O} on Grazing Angle.

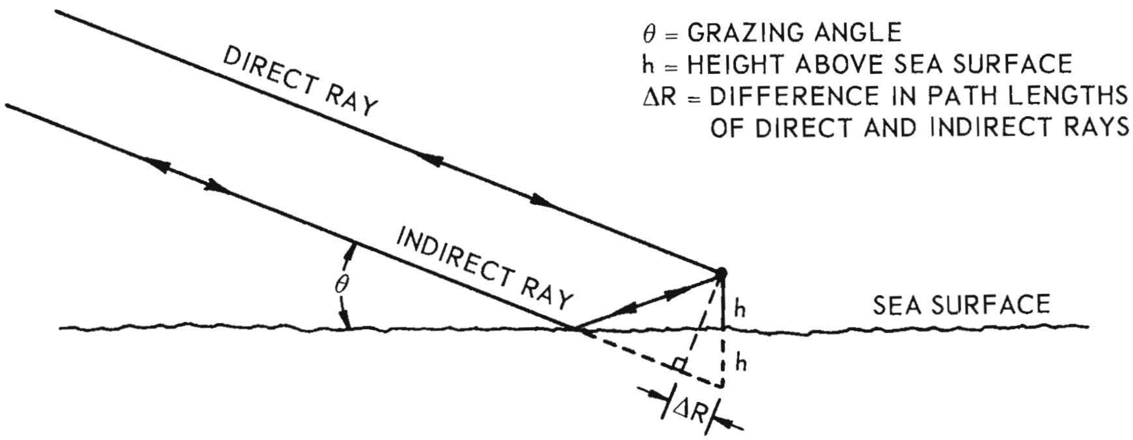

Figure 2. Interference Geometry.

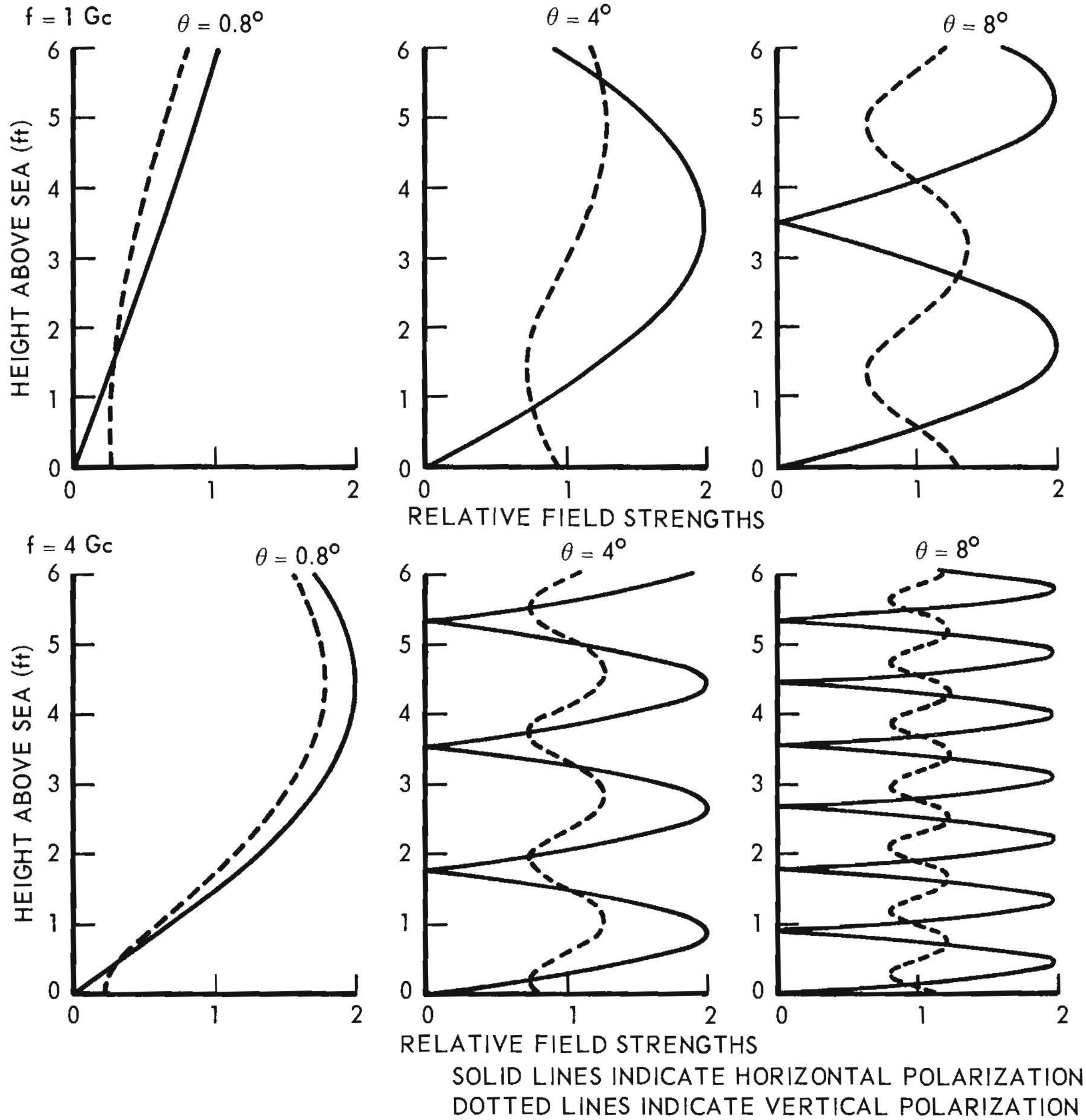

Figure 3. Electric Field Amplitude Patterns above a Smooth Sea Relative to the Field Amplitude in Free Space, at 1 and 4 Gigacycles for Grazing Angles 0.8°, 4°, and 8°. Data on the dielectric properties of sea water were taken from Saxton [1952].

as the sea becomes rougher. Beyond this angle, the higher antinodes dip into the region where the scattering elements lie. Because the statistical distribution of scattering-element heights is broad enough to span the nodes and antinodes of the interference pattern, the backscattering cross section does not oscillate perceptibly with further increase of grazing angle above θ_c. Instead it stabilizes into a smooth plateau.

The radar wavelength is intimately involved in this model of the phenomenon since the vertical distance between nodes proves to be proportional to wavelength. The advantage of long wavelengths in reducing sea scattering therefore is a result of lifting the first antinode out of the region occupied by the scattering elements. Beyond the critical angle, this advantage is lost, but it should be remembered that the critical angle is also increased by increasing the radar wavelength [Durlach, 1965].

The strong dependence of σ^o on wavelength for grazing angles less than the critical angle can be accounted for by the interference effect. Much of the experimental data on horizontal polarization indicate that σ^o varies about as θ^4 in this region; such behavior agrees with the predictions of the interference theory, provided that the radar cross section of the individual scatterers for a constant amplitude of illumination is independent of θ. Most of these data also indicate that for grazing angles below the critical angle σ^o increases rapidly as λ decreases. In some cases σ^o has been observed to vary as rapidly as λ^{-4}. The interference theory predicts a λ^{-4} dependency, provided that the radar cross section of the individual scatterers for a constant amplitude of illumination is independent of λ [Katzin, 1955].

2. Plateau Region

Various opinions [Kerr, 1951; Davies and Macfarlane, 1946; Katz, 1963] have been expressed regarding the interpretation of measurements on the angular dependence of σ^{o} in the plateau region, but it is generally concluded that the dependence of σ^{o} on grazing angle is "slight". It has been reasonably well established that the slope of σ^{o} versus θ depends on sea roughness and tends to become independent of θ for the rougher sea conditions [Katz, 1963]. Attempts have been made to describe the functional dependence of σ^{o} on θ and to correlate this dependence with theoretical models. Comparisons of experimental data with theoretical models have been inconclusive thus far, primarily because it has not been possible to obtain sufficiently accurate and/or sufficiently controlled measurements. Differences between experimental and theoretical results have not been considered significant because none of the proposed theoretical models have adequately fit the experimental conditions. On the other hand, the experimental results, taken as a whole, appear to be adequately consistent for predicting operational performance. The differences between the median value of σ^{o} obtained from all available data and the values obtained by the various investigators (for moderate to rough sea conditions and for various microwave frequencies) are not substantially greater than the differences between runs for an individual observer. The plateau region is discussed in greater detail in Section II.

3. Near Vertical Incidence

A substantial amount of work has been done at microwave frequencies to measure σ^{o} at large depression angles. The following general conclusions are reached by Spizzichino [Beckmann and Spizzichino, 1963] from data of

Cowan [1946], Maclusky and Davies [1945], Wiltse, et al. [1957], Macdonald [1956], Grant and Yaplee [1957], and Campbell [1959]. Pertinent references not cited by Spizzichino include Edison, Moore, and Warner [1960] and Williams, Bidwell and Bragg [1960]. For θ greater than θ_o (see Figure 1) and for frequencies in the microwave region:

(1) σ^o depends very little on the frequency and the polarization;

(2) σ^o rises more rapidly with increasing θ (that is, θ_o is smaller) the more agitated the sea, but reaches a lower peak at θ about 90°; thus for $\theta = 90°$, calm seas appear to have the greatest values of σ^o.

(3) For reception of the component of the return orthogonal to the transmitted radiation, σ^o appears to be about 10 to 15 db below the parallel component [Wiltse, 1957; Macdonald, 1956].

(4) σ^o is slightly larger for the upwind direction than for other directions.

C. Dependence of σ^o on Polarization

1. Transmitting and Receiving Horizontal and Vertical Polarizations

Changes in polarization have different effects on σ^o for different sea states or different wavelengths. For a calm sea, σ^o is usually larger for vertical polarization--occasionally by more than 20 db [Cowan, 1946; Kerr, 1951; Wiltse, et al., 1957]. For rougher seas the two σ^o's are more nearly equal, and under certain circumstances σ^o for horizontal polarization has been observed to exceed σ^o for vertical polarization. Goldstein [Kerr, 1951, pp. 495-499] states that observed values of the ratio $\sigma^o_{VV}/\sigma^o_{HH}$ varied between -8 db and +22 db for a collection of MIT Radiation Laboratory observations at 9.2 cm and 3.2 cm for θ between 0.65° and 1.35°. These measurements are considered quite accurate since all significant system errors cancelled when the ratios were taken. A definite correlation of this ratio with sea state was found. Large values of the ratio were found only when the sea was calm, and as the sea became rougher, the ratio steadily decreased to about unity for very rough seas at 9.2 cm. However, at 3.2 cm and very rough seas, the horizontal cross section was observed to be the larger.

For small grazing angles, sea clutter as displayed on a radar A-scope generally exhibits a more spiky appearance for horizontal polarization than it does for vertical polarization [Boring, et al., 1957; Macdonald, 1957]. The display for vertical polarization is characterized principally by a noise-like appearance, although some spikes may be visible. With horizontal polarization, under certain conditions (calm seas viewed with high resolution radar) the spikes are quite prominent and tend to persist at higher grazing angles than any spikes observed with vertical polarization. The frequency spectrum obtained at X-band with a coherent radar was reported by Hicks et al. [1960].

The fact that at low grazing angles the polarization dependence of σ^0 changes with sea state or wave height suggests that the polarization dependence is caused by the differences in the interference patterns of the two different polarizations.

At larger grazing angles (in the plateau region) σ^0 is usually larger for vertical polarization than for horizontal, but the interference explanation does not apply to these grazing angles [Katz and Spetner, 1960]. A few exceptions have been reported by several investigators who have measured greater returns for horizontal than for vertical polarization [Boring, et al., 1957; Kerr, 1951, p. 512; Katz and Spetner, 1960]. At X-band σ^0 for vertical polarization may be as much as 15 db greater than for horizontal in calm seas for angles in the plateau region, with the ratio decreasing to 3 or 4 db for wind speeds around 20 knots. At L-band the ratios vary from about 25 db in a calm sea to 11 or 12 db in a 20-knot wind [Macdonald, 1963].

At incidence angles near the vertical, the terms "horizontal and vertical polarization" lose their meanings since when $\theta = 90°$ the electric field vectors in both cases lie in the horizontal plane. As one would expect, the differences between σ^o for "horizontal" and "vertical" polarization vanish as θ approaches 90°.

2. Cross Polarized Echoes

The component of a radar echo whose polarization is orthogonal to the transmitted radiation is called the cross polarized component of the echo. Since the transmission properties of the atmosphere and the reflection and scattering properties of sea water are bilateral and linear, the instantaneous cross sections for cross polarized echoes, σ^o_{HV} and σ^o_{VH}, are equal. (The first subscript refers to the polarization of the transmitted radiation, the second to that of the received radiation.) Data taken by Georgia Tech [Boring, et al., 1957] indicate that σ^o_{HV} and σ^o_{VH} vary about as the cube of the wind speed but are independent of the wave height. This strong dependence on wind speed suggests that wind generated ripples, which have comparatively short radii of curvature and sharp edges, are the major cause of depolarized echo.

Measurements indicate that σ^o_{HV} is about 5 to 10 db less than σ^o_{HH} for moderately small grazing angles [Boring, et al., 1957] and that the difference increases with θ to a value nearer 20 db at vertical incidence [Wiltse, et al., 1957]; and that the difference between σ^{o}_{VV} and σ^{o}_{VH} is close to 15 db at moderately small grazing angles, with the difference increasing only slightly--to about 20 db--at vertical incidence.

3. Circular Polarization

Circular polarization is commonly used to reduce echo from rain, but the amount of available sea echo data for circular polarization is considerably less than that for linear polarizations. For this reason, the Appendix was prepared to provide equations which are useful for predicting the magnitude of circularly polarized echoes from results obtained for horizontal and vertical polarizations.

It is well known [Skolnik, 1962, pp. 547-551] that if the same circular polarization antenna is used for transmitting and receiving, echoes from targets are usually enhanced relative to those from rain. This is because the reflected energy from targets is generally mixed between two oppositely rotating polarized waves, but the energy reflected from rain is almost entirely of the circularity that will not be received. Gent and others [1963] recently published results on studies of rain rejection at X-band and 35 gc. McFee and Maher [1959] have presented estimates of the reduction in rain clutter cancellation caused by reflections off of a smooth sea. Curry [1965] has reported that the echo for clouds at UHF and L-bands is also substantially reduced by using circular polarization. Curry also discusses sea echo at very small grazing angles for UHF and L-band. Wiltse, et al. [1957], reported results obtained at 24 gc for σ^{o}_{HH}, σ^{o}_{VV}, σ^{o}_{VH}, and σ^{o} for receiving right circular and left circular polarizations when transmitting circular polarization (σ^{o}_{12} and σ^{o}_{11} or σ^{o}_{22} in the notation of the Appendix). The data were collected for a moderately heavy sea and a 26-knot wind and for various grazing angles between 15° and 90° (normal incidence). The data for the various polarizations could not be measured simultaneously and, therefore, it is unrealistic to make precise comparisons between the relative magnitudes for the various polarizations. For $\theta = 15°$, σ^o_{VV} was reported to be possibly 7 db greater than σ^o_{HH}, and σ^o_{HH} was possibly 7 db greater than σ^o_{VH} (or σ^o_{HV}). The values of σ^o for the two circularly polarized echoes were approximately equal to that of σ^o_{HH}. The relative magnitudes of σ^o for the various polarizations seem to be consistent (see Case III of the Appendix) in the light of the experimental difficulties involved.

The data indicate smooth changes between the variously polarized echo components as a function of grazing angle. For increased grazing angles, all of the values of σ^o increased but the differences (in db) between σ^o_{VV}, σ^o_{VH} (or σ^o_{HV}), and σ_{11} (or σ_{22}) remained approximately constant. As expected, σ^o_{HH} increased with angle more rapidly than did σ^o_{VV}, and σ^o_{HH} was approximately equal to σ^o_{VV} at normal incidence. It is interesting to note that σ^o_{12} at normal incidence was approximately equal to σ^o_{VV} and σ^o_{HH}. Suppose that a_{VV} and a_{HH} were incoherent as in Case II of the Appendix. Then the relative magnitudes of the two circularly polarized components of the echo should be equal. The measured values differed by about 10 db.

For angles near normal, it is expected that the phases and amplitudes of the VV and HH fields after reflection will tend to be equal on an instantaneous basis. This is because the complex reflection coefficients for the two polarizations at an air-water interface [Povejsil, et al., 1961, pp. 184-185] are slowly varying functions of the angles and are nearly equal for normal incidence. Therefore, it is expected that on the average

$$|a_{VV} + a_{HH}|$$

is approximately

$$2|a_{VV}| \quad \text{or} \quad 2|a_{HH}|$$

Further

$$|a_{VV} - a_{HH}|$$

is expected to be smaller than either

$$|a_{VV}| \quad \text{or} \quad |a_{HH}|$$

but

$$|a_{VV} - a_{HH}|$$

is not expected to be zero because a_{VV} will not be equal to a_{HH} in both phase and amplitude at all times. The results expected for a_{VV} identically equal to a_{HH} are given as Case I in the Appendix. Note that the experimental results reported by Wiltse, et al. [1957], are consistent with the above hypothesis that for near normal incidence a_{VV} and a_{HH} tend to be equal on an instantaneous basis but that a_{VV} and a_{HH} are not identically equal for all times.

Curry [1965] reports very small values of σ^o (approximately -100 db) for circular polarization and very small grazing angles at UHF and L-band. This unusually small value of σ^o is not a characteristic of circular polarization, per se. Curry reported that under his operating conditions σ^o_{VV} is much greater than σ^o_{HH}. Therefore, according to Case III of the Appendix, the return for circular polarization will be no less than 6 db smaller than σ^o_{VV}

and will thus be greater than σ^o_{HH}. Hence, it is apparent that the small σ^o reported by Curry results from the geometry involved because there is no indication that σ^o_{VV} (within the plateau region) at L-band is greatly different from that at the higher microwave frequencies.

As shown in the Appendix, the backscattered electric field for circular polarization (or any other polarization) is a linear combination of the fields that would be received for transmitting horizontal and vertical polarizations and receiving these two polarizations. Therefore, the dependences of circularly polarized echo on grazing angle, sea state, wind speed, and wavelength will be more clearly understood as questions regarding these dependences for the linear polarizations are resolved. Although the use of circular polarization has been shown to provide substantial improvement in target echo relative to cloud and rain clutter, no such improvement is to be expected for sea echo.

D. The Sea and Dependence of σ^o on the Sea

1. Dependence of σ^o on the Sea Surface

It is difficult to obtain accurate quantitative information concerning the influence of the sea state on σ^o since the parameters of the sea are difficult to measure; also, the effects of the various parameters on radar return are not well understood. Factors which can influence the character of the sea surface include the period and shape of the waves, the wave height, the wind, and the presence or absence of whitecaps and spray. However, most data indicate that the value of σ^o will in general increase as the sea becomes rougher for all grazing angles except those very near vertical incidence.

For small grazing angles Davies and Macfarlane [1946] observed a rapid increase in σ^o as the ocean wave height increased, until a sort of "saturation" set in. At X-band, the saturation height has been observed to be about 2 or 3 feet [Skolnik, 1962, p. 532], and as the radar wavelength increases, the saturation height increases. Such behavior is consistent with the interference theory. Other investigators [Boring, et al., 1957] have observed sudden increases in σ^o (as much as 10 db in a one-minute interval) for a sea with a 2-foot average wave height at the time of an abrupt increase in wind speed. Empirical formulas fitted to their data indicate that for small grazing angles (less than 4°) σ^o varies about as the cube of the wind speed for horizontal polarization and as the square of the wind speed for vertical polarization. The dependence on wave height was much weaker. Other observers [Schooley, 1956] have reported for horizontal polarization that "σ^o is very approximately proportional to the local wind velocity squared." These facts suggest that the principal scattering mechanism of the sea is connected with its fine structure although interference effects may still be present. It appears that there may be a saturation effect with wind speed similar to the saturation effect with wave height. For example, σ^o is less sensitive to a 5-knot change in wind speed at 25 knots than at 10 knots.

In the plateau region, σ^o increases with increasing wind speed [Kerr, 1951, p. 512; Wiltse, et al., 1957] but at vertical incidence the trend is reversed. For depression angles less than about 70°, an increase in wind speed from 5 to 25 knots can increase σ^o by more than 20 db in the 15 to 35 kmc frequency range [Grant and Yaplee, 1957].

Virtually all investigators using microwaves agree that σ^o is greatest when the antenna is looking directly into the wind. The increase over the downwind direction is frequently as great as 5 db, and sometimes as much as 8 db for small and moderate grazing angles (see Figure 8). Looking across the wind, σ^o seems to be about the same as for the downwind direction.

2. Nature of the Sea Surface

In order to arrive at a reasonable understanding of sea return, one must have at least a rough physical description of the sea surface, even though it is not perfectly clear what surface characteristics are responsible for sea return. Qualitatively, the basic characteristics of the sea surface are well known: large-scale, roughly periodic waves, upon which ripples, foam, and spray are superimposed. The large waves are commonly called the macrostructure, and ripples and the like, the microstructure of the sea surface. The macrostructure of the sea is usually described by specifying the "sea" and the "swell". "Sea" consists of relatively steep short-crested waves produced and driven by the winds in their locale and are called wind waves. "Swell" consists of waves of long wavelength, nearly sinusoidal in shape, and are produced by distant winds. The very irregular appearance of the sea surface is due to interference of the various wind and swell waves and to local atmospheric turbulence. Ocean currents have only a slight effect on the characteristics of the sea surface except along the coast lines. Near a coast, currents (usually tidal currents) may cause considerable increase in wave heights due to their interference with wind and swell waves. Foam and spray are largely caused by interference, while ripples are usually caused by turbulent gusts of wind near the surface.

There have been two qualitative sea-state scales in general use. The one used exclusively before World War II, and a great deal of the time during and after, is the Beaufort scale. It would be better named Beaufort wind scale since it is based on wind force and not wave height. This scale is given in Table I*. Wave height depends not only on local wind force but also on the length of time and the length of sea over which the wind has been blowing.

The Douglas scale, shown in Table II, is more descriptive than the Beaufort scale in that the sea is specified by wave height; in this scale's best form, the sea and swell are measured independently. The complete Douglas scale attaches two numbers to every sea state; a short form, which is frequently used, gives only the "sea" number.

3. Statistical Analysis of the Sea Surface

Examples of measured wave height distributions given by Watters [1953] are shown in Figure 4. These distributions vary in shape with the mean wave height $\bar{H}$. In smooth seas (Figure 4 (a)), the histogram tends to be peaked, indicating a high probability of waves having heights near the average. For rough seas (Figure 4 (b)), the distribution is usually broader, indicating many waves with heights differing from the mean height $\bar{H}$. There is a third general type (Figure 4 (c)) in which the distritution has a minimum near $\bar{H}$. In general, however, the shape of the curve for all sea states is found to be fairly well represented by a curve [Watters, 1953] of the form

$$y_i = \frac{N}{\sigma^2} x_i \exp\left(-x_i^2/2\sigma^2\right)$$

where y_i = number of waves occurring in the i-th wave-height interval,

x_i = the mean wave-height in the i-th interval,

*Taken from a more detailed table given on page 37 of Undersea Technology, May, 1964.

TABLE I
WIND AND WAVE SCALES

WIND SPEED (KNOTS)	4	5	6	7	8	9	10	15	20	25	30	40	50	60	70

WIND AND DESCRIPTION (BEAUFORT SCALE)	1 LIGHT AIR	2 LIGHT BREEZE	3 GENTLE BREEZE	4 MODERATE BREEZE	5 FRESH BREEZE	6 STRONG BREEZE	7 MODE-RATE GALE	8 FRESH GALE	9 STRONG GALE	10 WHOLE GALE	11 STORM

REQUIRED FETCH (MILES)	FETCH IS THE NUMBER OF MILES A GIVEN WIND HAS BEEN BLOWING OVER OPEN WATER	50	100	200	300	400	500	600	700

REQUIRED WIND DURATION (HOURS)	DURATION IS THE TIME A GIVEN WIND HAS BEEN BLOWING OVER OPEN WATER	5	20	25	30	35

IF THE FETCH AND DURATION ARE AS GREAT AS THOSE INDICATED ABOVE, THE FOLLOWING WAVE CONDITIONS WILL EXIST. WAVE HEIGHTS MAY BE UP TO 10% GREATER IF FETCH AND DURATION ARE GREATER.

WAVE HEIGHT CREST TO TROUGH (FEET)	1	2	4 WHITE CAPS FORM	6	8	10	15	20	25	30	40	50	60

SEA STATE AND DESCRIPTION (DOUGLAS SEA NUMBER)	1 SMOOTH	2 SLIGHT	3 MODE-RATE	4 ROUGH	5 VERY ROUGH	6 HIGH	7 VERY HIGH	8 PRECIPITOUS

THE HEIGHT OF THE WAVES IS ARBITRARILY CHOSEN AS "THE HEIGHT OF THE HIGHEST 1/3 OF THE WAVES."

TABLE II

THE COMPLETE DOUGLAS SCALE

Sea No.	Description	Wave Height in Feet	Swell No.	Approximate Height in Feet	Description		Approximate Length in Feet
0	Calm	0	0	0	No swell		0
1	Smooth	<1	1	1-6	Low swell	Short or average	0-600
2	Slight	1-3	2			Long	Above 600
3	Moderate	3-5	3	6-12	Moderate	Short	0-300
4	Rough	5-8	4			Average	300-600
5	Very rough	8-12	5			Long	Above 600
6	High	12-20	6	>12	High	Short	0-300
7	Very high	20-40	7			Average	300-600
8	Mountainous	40 and over	8			Long	Above 600
9	Confused		9	---	Confused		

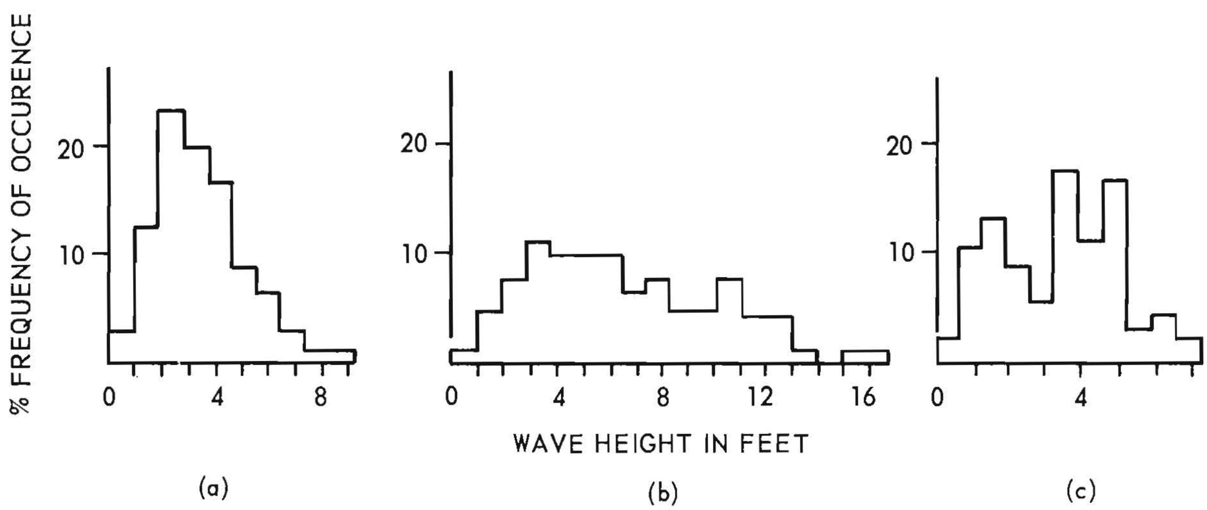

Figure 4. Waveheight Distributions.

N = total number of wave record observations,

and $\sigma^2 = \frac{2}{\pi^2}\bar{H}^2$.

Another listing of wave-height distributions taken from a publication of the U. S. Navy Hydrographic Office [1947] is shown in Table III. These distributions are based on over 40,000 extracts from ships' log books and are in fair agreement with the data of Watters.

The U. S. Navy Marine Climatic World Atlases [Naval Aerology Branch, 1957] provide detail surface wind data for the North Atlantic, North Pacific, and Indian Oceans for all months of the year. These data have been collected over a period of years from island, coastal, and ship weather stations. The surface wind data, presented in frequency distributions of Beaufort Force, were analyzed by averaging over all oceans and months of the year and the results are presented in Figure 5. The surface wind probability density function is plotted in Figure 5 (a); Figures 5 (b) and 5 (c) were obtained from Figure 5 (a).

TABLE III

RELATIVE FREQUENCY OF WAVE HEIGHTS IN REGIONS OF THE WORLD

Region	Height of waves in feet					
	0-3 (%)	3-4 (%)	4-7 (%)	7-12 (%)	12-20 (%)	>20 (%)
North Atlantic, between Newfoundland and England	20	20	20	15	10	15
Mid-equatorial Atlantic	20	30	25	15	5	5
South Atlantic, latitude of southern Argentina	10	20	20	20	15	10
North Pacific, latitude of Oregon and south of Alaskan Peninsula	25	20	20	15	10	10
East-equatorial Pacific	25	35	25	10	5	5
West Wind Belt of South Pacific, latitude of southern Chile	5	20	20	20	15	15
North Indian Ocean, Northeast monsoon season	55	25	10	5	0	0
North Indian Ocean, Southwest monsoon season	15	15	25	20	15	10
Southern Indian Ocean between Madagascar and northern Australia	35	25	20	15	5	5
West Wind Belt of southern Indian Ocean on route between Cape of Good Hope and southern Australia	10	20	20	20	15	15
Averages over all regions	22	23	20.5	15.5	9.5	9.0

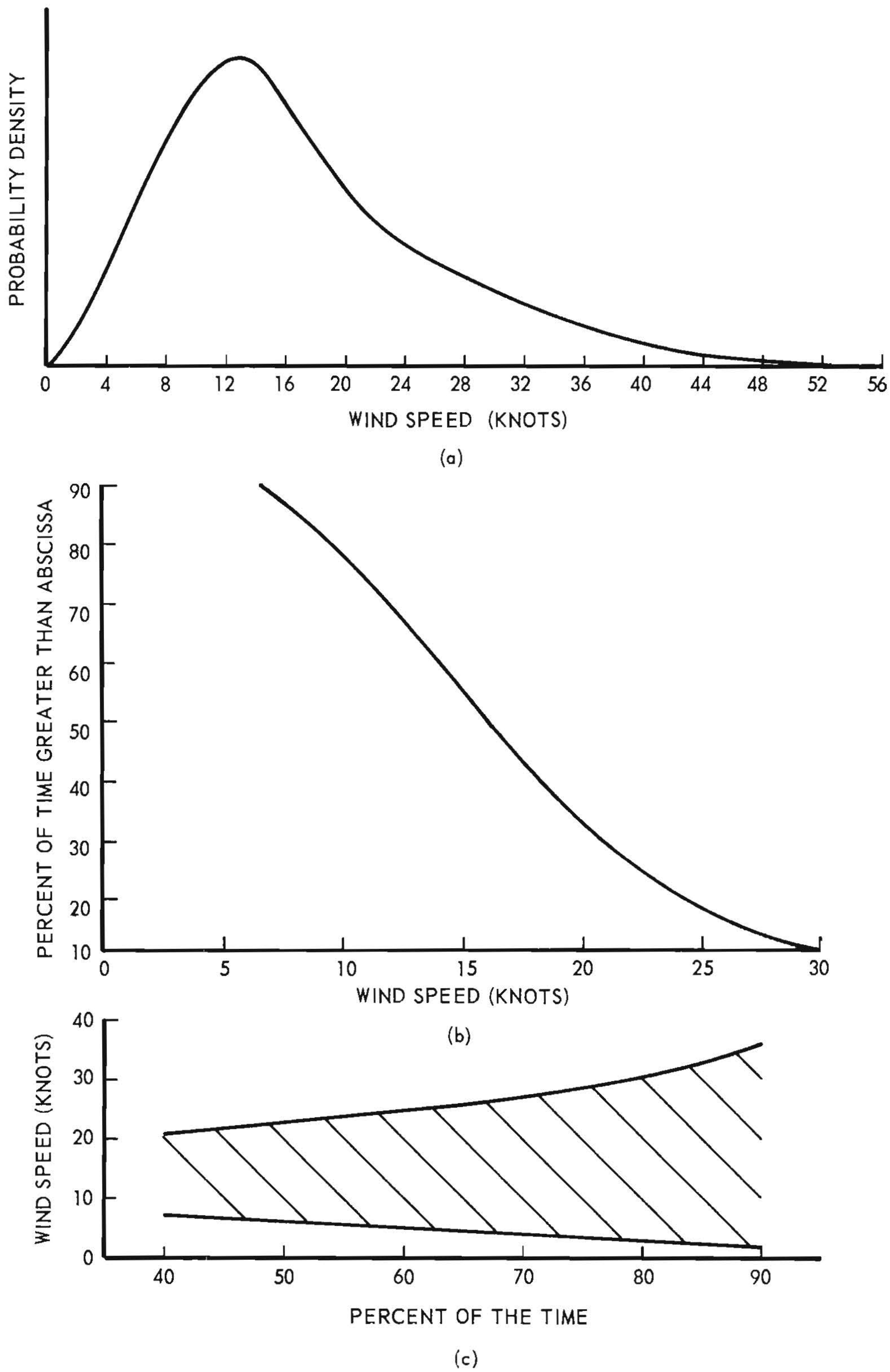

Figure 5. Surface Wind Speed Statistics.

II. SEA ECHO FOR MICROWAVES

A. Measurements

Although a large quantity of sea echo data has been reported by numerous investigators, the wide variability of the data makes analysis difficult. This variability is due to a number of reasons. Measured values of σ^O are sensitive to the character of the sea surface (whose variations are uncontrollable and can occur quite rapidly) and to variations among measuring equipments and their calibration. In order to understand sea echo, measurements of the sea surface are required in addition to measurements of the sea echo. Problems in making all these measurements have tended to obscure any correlation which may exist between σ^O and wavelength for various sea states. Often, even the most rudimentary description of the sea surface (wave height, wave direction, wind speed, wind direction, or a qualitative description) has not been reported, not only because the measurements are difficult but also because no one knows precisely what characteristics of the sea surface are important to the sea echo problem.

Obtaining a valid description of the dependence of radar cross section on wavelength is difficult because one must make measurements simultaneously with at least two radars, and, in addition, make quantitative sea measurements. The radars must be accurately calibrated with respect to one another; preferably, redundant absolute calibrations should be available for the two or more radars. Almost no data of this type exist. Since the available descriptions of the sea are at best very crude, it is virtually hopeless to obtain meaningful results by comparing data at one wavelength from one observer with those at some other wavelength from another observer. The problem is further complicated by the rapid time variations in σ^{O} which can occur. Observations at a single wavelength indicate that radar cross section can change as much as 10 db in a one-minute interval. The measurement errors and uncertainties tend to obscure the weak functional relationship that apparently exists between σ^{O} and λ for most grazing angles.

In spite of the fact that none of the existing data are of the quality that would be desirable, the data do indicate trends concerning the dependence of σ^{O} on wavelength. This dependence cannot be stated as a simple functional relationship between σ^{O} and λ because the dependence varies with both the sea state and the angle of arrival. For example, the dependence on angle of arrival is quite noticeable for the small grazing angles below the critical angle, where the interference effect makes σ^{O} a strong function of wavelength. Sea echo for this region is discussed in detail by Spizzichino [Beckmann and Spizzichino, 1963] and Katzin [Povejsil, et al., 1961, Chapter 4]. At the larger grazing angles, near vertical incidence, the value of σ^{O} is highly dependent on sea state and actually decreases as the roughness of the sea increases. Spizzichino also discusses sea echo for large grazing angles in detail.

Various opinions have been expressed regarding the dependence of σ^{O} on θ in the plateau region (which for microwaves extends at least from 5° to 50°), but it is generally concluded that the dependence of σ^{O} on grazing angle is "slight". It is reasonably well established that for the plateau region the slope of σ^{O} versus θ depends on sea roughness; σ^{O} tends to be independent of θ for the rougher sea conditions [Katz, 1963]. Therefore, the plateau region is particularly attractive for a study of wavelength dependence because the effect of θ, one of the many variables, is at a minimum.

B. Grazing Angle Dependence

Attempts have been made to describe the functional dependence of σ^o on θ and to correlate this dependence with theoretical models. Such interpretations have been inconclusive because it has not been possible to obtain data which were sufficiently accurate and made under adequately controlled conditions. On the other hand, the experimental results appear to be adequately consistent for predicting operational performance.

Figures 6 and 7 show a collection of experimental results obtained for σ^o_{VV} versus θ for frequencies from 1.2 Gc to 35 Gc and for wind speeds of 10 knots and greater. Note that when these data are considered as a whole, there is good consistency in the slopes of 10 log σ^o_{VV} versus θ obtained by individual observers. In addition, the differences between the median of all data presented and the absolute values obtained by various investigators are not substantially greater than the differences obtained on different runs by one observer. Thus, it is apparent that the slope of σ^o_{VV} versus θ for engineering purposes is independent of wavelength; also these data suggest no strong correlation of σ^o_{VV} with wavelength for any specific value of θ within the plateau region. The medians of the data shown in Figures 6 and 7 are essentially straight lines between 5° and 50° and have slopes of roughly 1/4 db per degree. Thus, even though the variation of σ^o versus θ in the plateau region is small, there is still a non-negligible increase of approximately 10 db when the grazing angle is increased from 5° to 45°.

Figure 8 shows a collection of results obtained for σ^o_{HH} versus θ for wind speeds of 10 knots and greater. Fewer σ^o_{HH} data than σ^o_{VV} data were available; the σ^o_{HH} curves are included for completeness and should not be used to compare σ^o_{HH} with σ^o_{VV} of Figures 6 and 7. The slope of the median

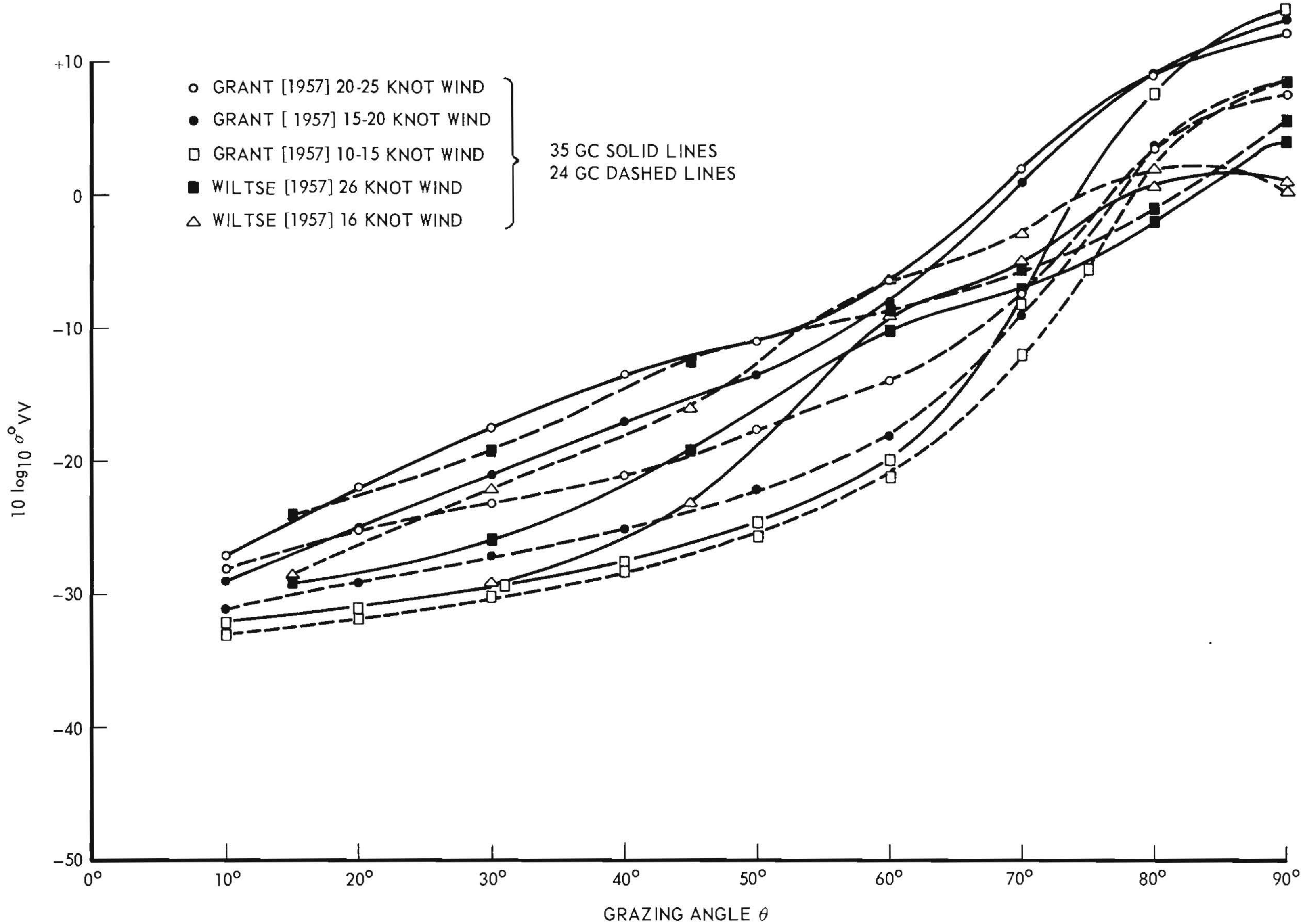

Figure 6. Measured Values of σ^{o}_{VV} Versus Grazing Angle.

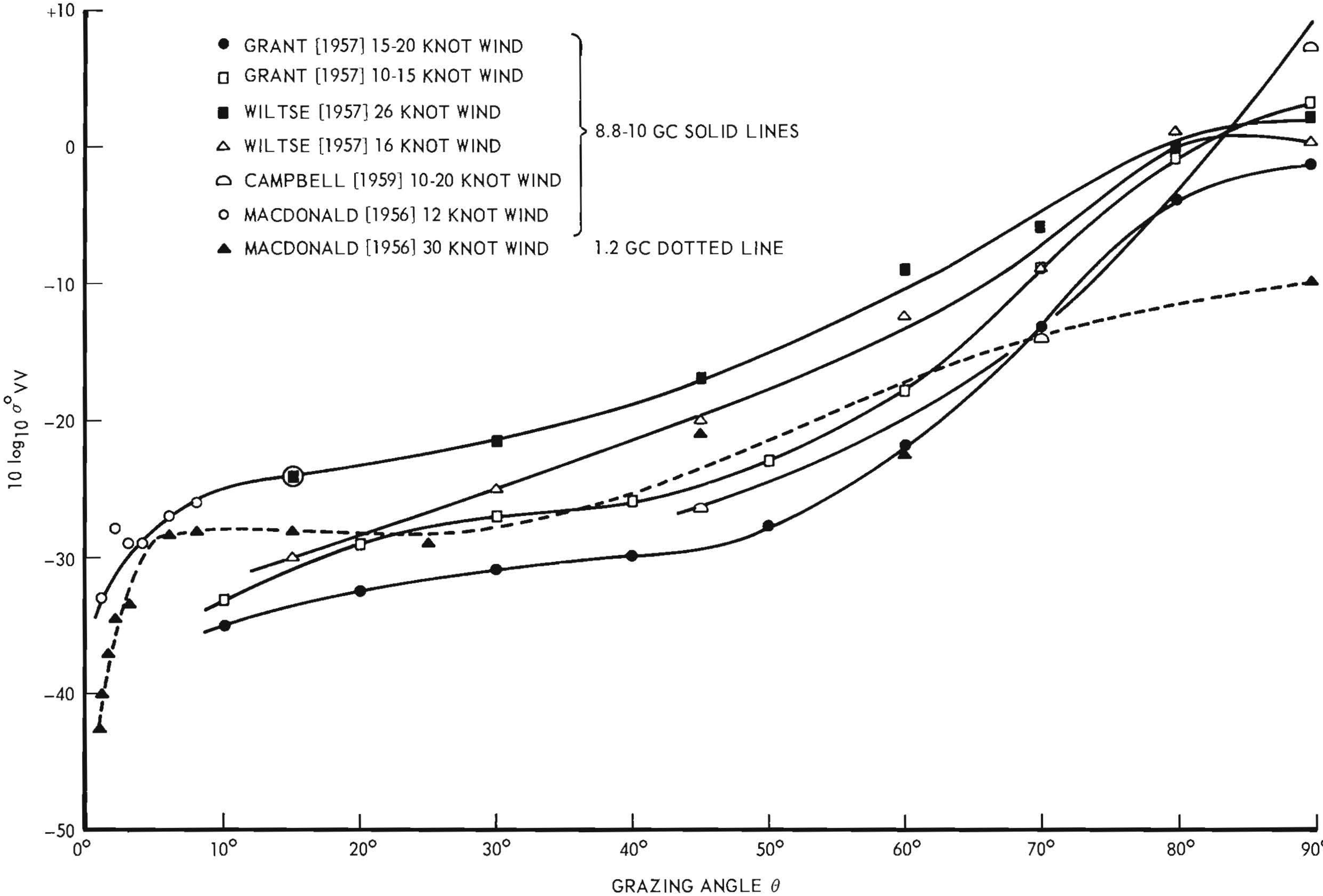

Figure 7. Measured Values of σ^{o}_{VV} Versus Grazing Angle.

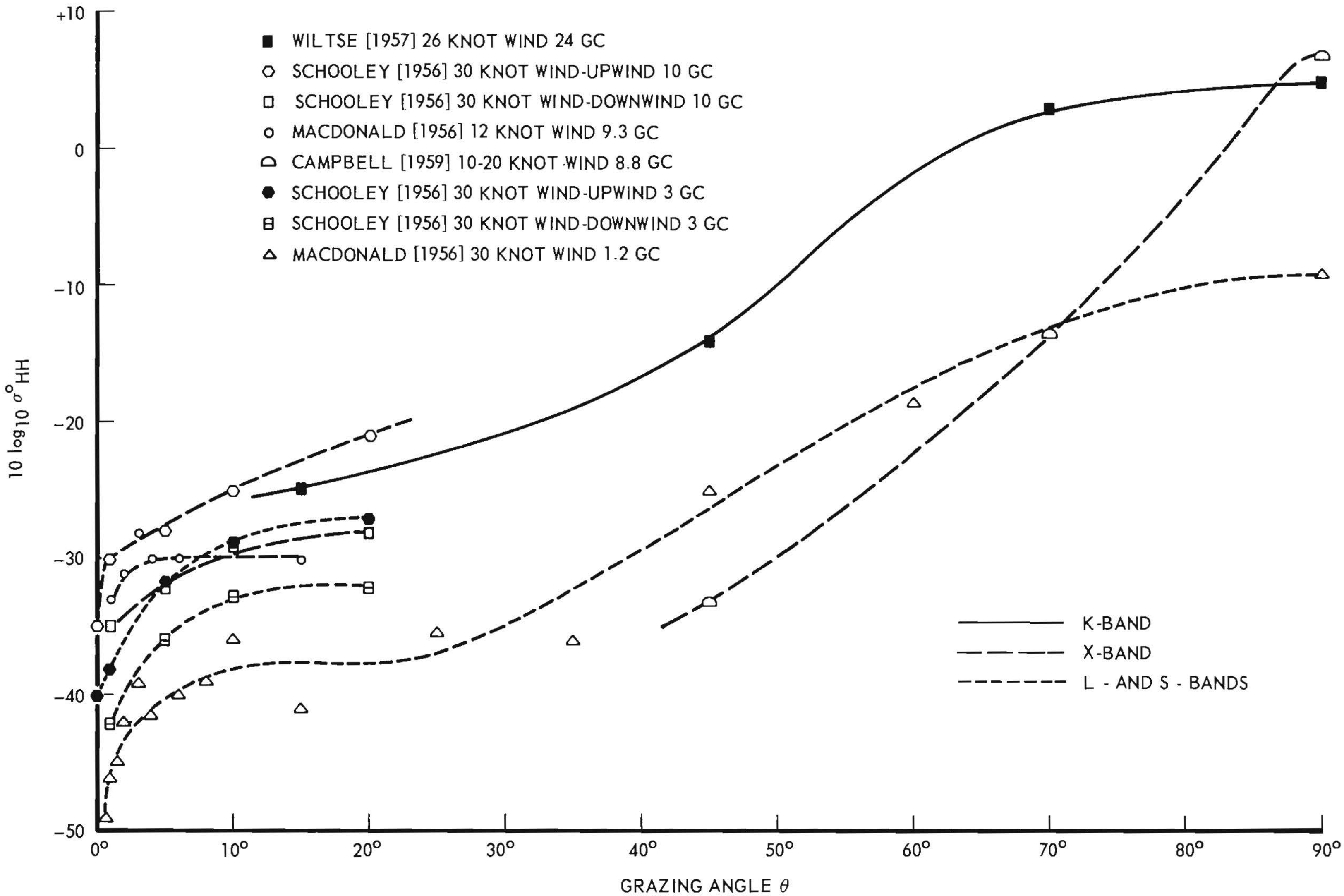

Figure 8. Measured Values of σ^{o}_{HH} Versus Grazing Angle.

of the curves probably is not much different than that for the σ^o_{VV} curves. Relative measurements provide a much more accurate comparison of σ^o_{VV} with σ^o_{HH} since most calibration errors do not affect the ratio $\sigma^o_{VV}/\sigma^o_{HH}$, whereas Figures 6, 7, and 8 show absolute data taken at different times by different experimenters.

There have been numerous comparisons of the relative values of σ^o_{VV} versus σ^o_{HH}. Goldstein [Kerr, 1951] discussed the two in detail for the smaller angles; more recently Macdonald [1963] reported results over a wide range of grazing angles for wavelengths of 24 cm and 3 cm (see Figure 9). It is generally recognized that the following statements hold for the ratio $\sigma^o_{VV}/\sigma^o_{HH}$ in the plateau region: (1) the ratio increases with an increase in wavelength, and (2) the ratio decreases with an increase in sea roughness. Macdonald reports that even at X-band and for wind speeds of 10 knots or more, σ^o_{HH} will be several decibels less than σ^o_{VV}. For L-band, Macdonald's results indicate that σ^o_{HH} will be at least 10 db less than σ^o_{VV} for all measured wind speeds over the range of grazing angles of approximately 5° to 30°.

C. Sea Echo Prediction

Empirical formulas fitted to Georgia Tech data [Boring, et al., 1957] for 6.3 Gc indicate that σ^o varies approximately as the cube of the wind speed for horizontal polarization and as the square of the wind speed for vertical polarization. The data which were for grazing angles between 1.5° and 4.0°, indicated that σ^o was not strongly dependent on angle. A small but statistically significant dependence on wave height (σ^o increases slightly with increases in wave height) was found for the HH echo. Essentially no dependence on wave height was observed for VV and VH echoes, the other polarizations investigated.

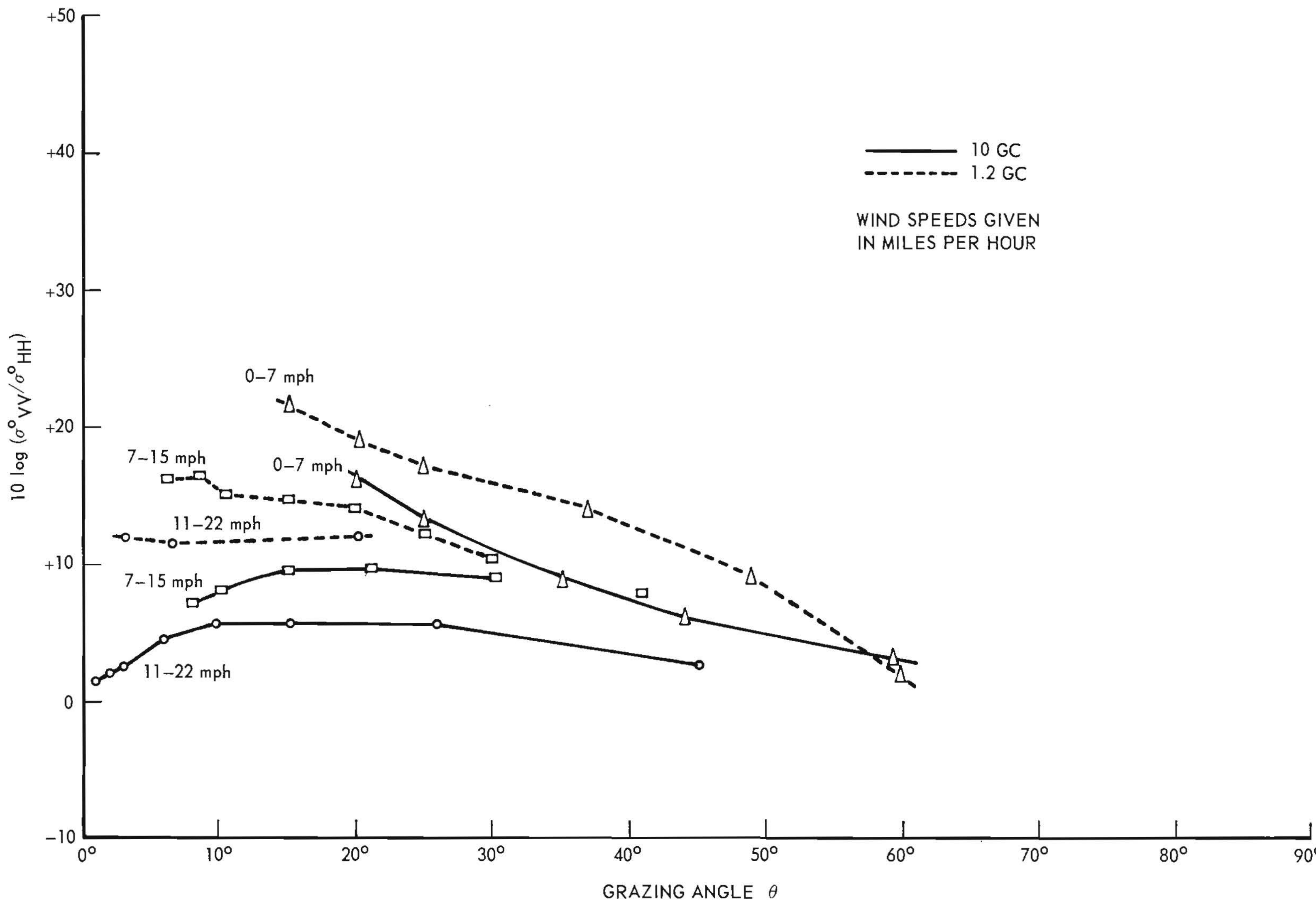

Figure 9. Ratio of Sea Echo on Vertical Polarization to that on Horizontal Polarization.

Prediction equations for grazing angles between 1.5° and 4.0° were obtained [Boring, et al., 1957, p. 36 and p. 39] by fitting the results of 198 measurements of σ^o_{VV} and σ^o_{HH} to empirical equations. At 4°, the largest angle for which measurements were made, these equations yield the following results:

$$10 \log \sigma^o_{VV} = 20.4 \log W + 7.45 \cos \beta - 64.0$$

$$10 \log \sigma^o_{HH} = 31.5 \log W + 9.8 \cos \beta - 81.4$$

where

W = wind speed in knots, and

β = wind aspect angle in degrees.

The wind aspect angle was defined as the angle between the line of sight and the wind direction so that for a wind aspect angle of zero degrees the antenna is looking into the wind. Due to the location of the radar equipment on a beach, aspect angles larger than 90° were rare. The data were collected during the execution of an extended field operation at Boca Raton, Florida. The site was located where the ocean depth varies between 25 and 40 feet over a range interval of 350 to 1500 yards. The data were for mean surface to peak wave heights up to 5 feet and wind speeds up to 20 knots; therefore, the equations may not be valid for wind speeds much greater than 20 knots. In general, the surface of the sea was characterized by short crested waves covered with chop; swell was observed on occasion. Local weather conditions and the shielding effect of offshore land masses normally precluded generation of deep sea waves within the radar range used. Antennas and associated items of equipment were placed on an elevator platform which permitted antenna heights to be varied between 35 and 124 feet above the sea surface. The limited radar range used minimized the effect of anomalous propagation conditions.

Using the surface wind data presented in Figure 5, predicted probability distributions of sea return can be made for θ equal to $4°$ with the above prediction equations. Figure 10 was prepared as a worst case prediction for β equal to $0°$. In accordance with the discussion in the section on grazing angle dependence, curves for other grazing angles in the plateau region can presumably be obtained by increasing σ^o by roughly 1/4 db for each degree of increase in θ above $4°$. For example, from Figure 10 (b) we see that 50% of the time sea echo for $4°$ and vertical polarization is expected to be between -29 db and -40 db. Therefore, for $44°$ and 50% of the time, σ^o is expected to be between -19 db and -30 db.

Figure 11 was prepared as a prediction of σ^o_{VV} in the plateau region with wind aspect angle equal to $0°$ and wind speeds of 10, 16, and 30 knots. The prediction equation given for θ equal to $4°$ was used as starting point and slopes of 1/4 db per degree were used in approximate agreement with the median of the data shown in Figures 6 and 7. It should be noted that there is general agreement between the predictions of Figure 11 and the measured data contained in Figures 6 and 7. Since no correlation of σ^o_{VV} with wavelength is apparent from Figures 6 and 7, it would appear that the prediction curves could be used as a guide for estimating σ^o_{VV} for all microwave frequencies.

Curves similar to Figure 11 but for σ^o_{HH} can also be drawn; the curves would indicate general agreement with the scanty amount of measured σ^o_{HH} data available for the plateau region. A set of prediction curves for σ^o_{HH} were not included because their inclusion would tempt some readers to use the σ^o_{VV} and σ^o_{HH} predictions to make detailed comparisons between the relative values.

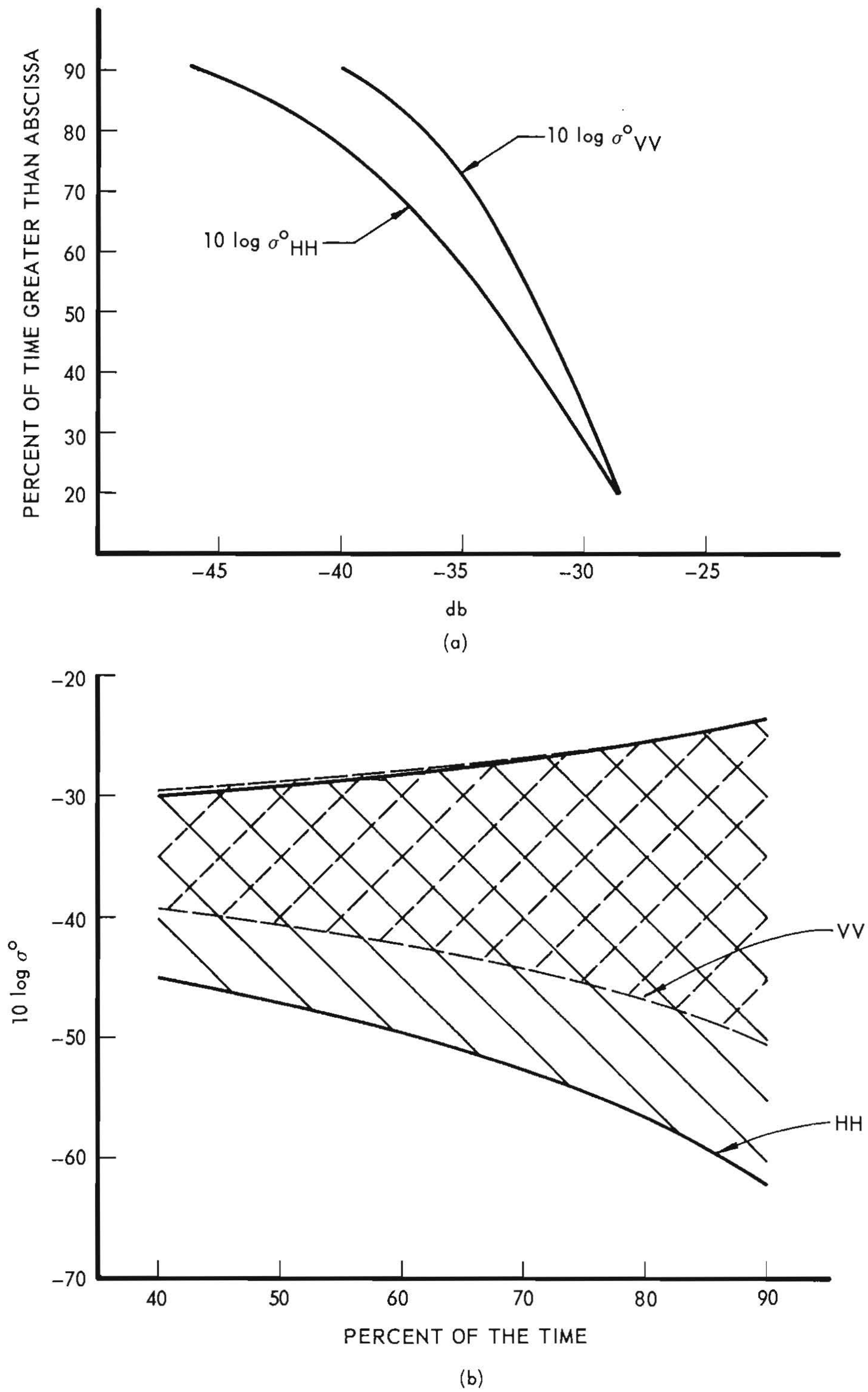

Figure 10. Radar Cross Section Predictions.

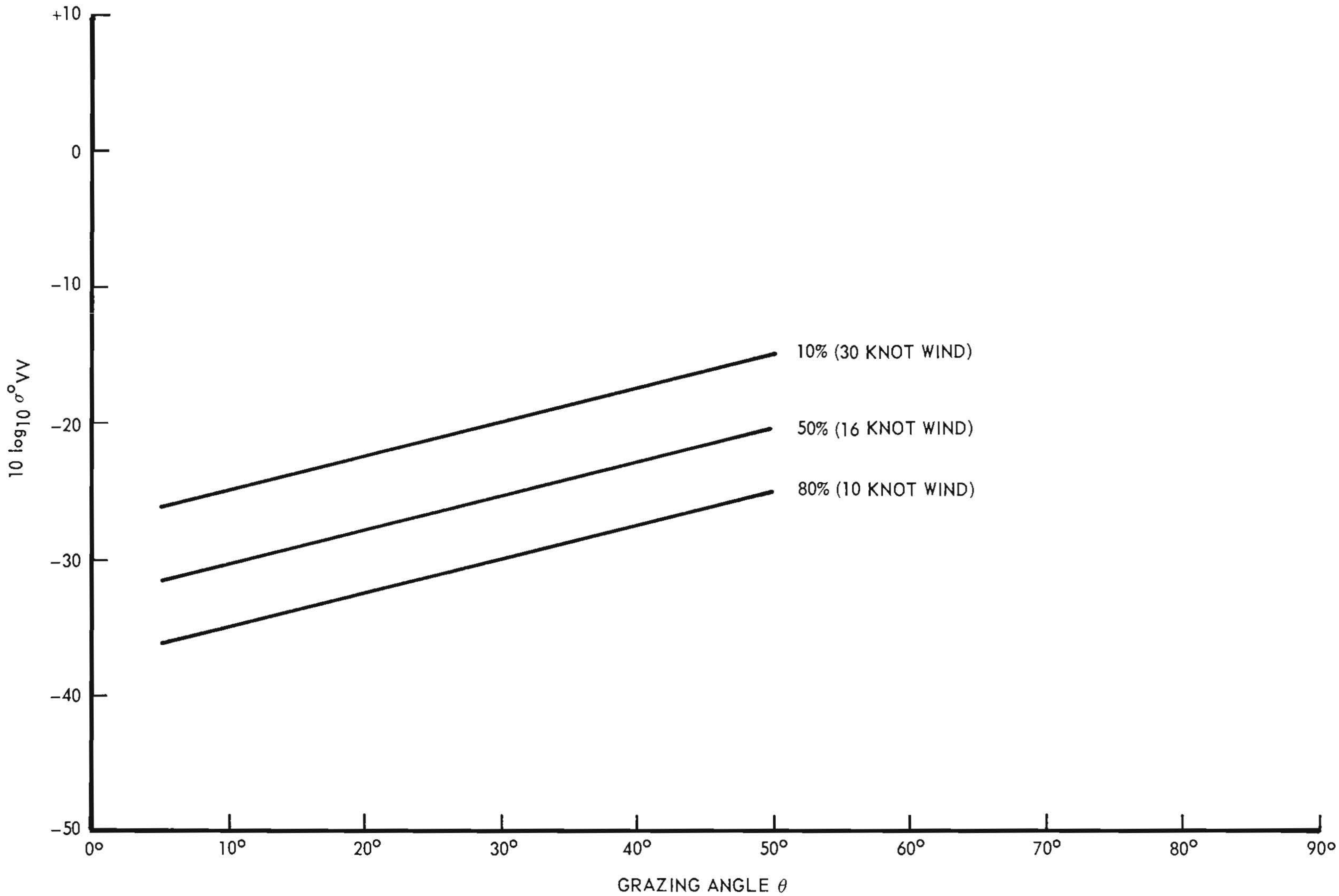

Figure 11. Predicted Values of σ^{o}_{VV} Versus Grazing Angle. Since surface wind speed exceeds 30 knots 10 per cent of the time, σ^{o}_{VV} is expected to exceed the 10% line 10 per cent of the time; similarly for the 50% and 80% lines.

It must be stressed that the prediction equations and curves are simply guesses of σ^{o} based on limited data. The prediction curves are included only to provide rough estimates on magnitudes and likely trends; they are untested approximations and are unreliable for use in detailed engineering analyses.

D. Wavelength Dependence

To study the effect of wavelength on σ^{o}, one generally compares the experimental values of σ^{o} for two values of λ. Thus, it is necessary to have data from two radars calibrated with respect to one another. It has been conventional to assume that σ^{o} is proportional to λ^{n} and to express the results in terms of the value of n.

Goldstein reported [Kerr, 1951] several experiments where the values of σ^{o} were compared either for wavelengths of 1.2 cm and 3.2 cm, or for 3.2 cm and 9 cm. The values found for n were highly variable; they depended on the state of the sea and on polarization. These measurements were for θ of 2° or less, corresponding to the "near grazing incidence" region and part of the "plateau" region in Figure 1. For calm seas and horizontal polarization, the increase in going from 10 to 3 cm ranged from 10 to 20 db. For rougher seas, little difference in σ^{o} was found between the wavelengths although Goldstein reported [Kerr, 1951, p. 511] that the echo may even be a bit smaller (2 db) at 3 cm. For vertical polarization, there was also an increase in σ^{o} in going from 10 to 3 cm; for calm seas the increase was never more than 10 db, and as the sea became rougher, the ratio was found to become smaller. For moderate or rough seas, the echo at 3 cm was sometimes weaker by as much as 5 db.

The authors know of no measurements that have been reported in recent years for which n is positive, as was reported by Goldstein for the rough sea conditions. Further, no plausible scattering mechanism has been envisioned that would explain an increase in σ^{o} with an increase in wavelength. If the above measurements are considered to have a possible experimental error of $\pm$ 5 db (Goldstein [1950] indicated that no wartime results can be trusted to better than $\pm$ 5 db), the dilemma regarding the positive value of n is removed.

Goldstein also described [Kerr, 1951, p. 511] measurements made at the Telecommunications Research Establishment (Great Britain) for 3.2 and 1.25 cm for horizontal polarization. Two systems at 1.25 cm and one system at 3.2 cm were calibrated absolutely by means of a standard target consisting of a sphere suspended from a balloon. The ratio of the cross sections at the two wavelengths $\sigma^{o}(1.25)/\sigma^{o}(3.2)$ was independent of θ in the range measured and independent of waveheight above 2 feet. The values obtained for the ratio under these conditions were +3 db using one of the 1.25 cm systems and +7 db using the other. The difference of the values is an indication, perhaps, of the accuracy of the absolute calibration. The smaller value is stated to be the more reliable and is considered to be indicative of a variation as $1/\lambda$. These measurements are presumably those included in a report by Davies and Macfarlane [1946]. The authors of that paper stated that under rough sea conditions, measurements at 10 cm, 3 cm, and 1.2 cm indicated a λ^{-1} dependence on σ^{o}. More recently Katzin [1957] reported that measurements he had reviewed also indicated a wavelength dependence close to λ^{-1}. The measurements described above were for small grazing angles.

Wiltse, Schlesinger, and Johnson [1957] obtained data for horizontal, vertical, and circular polarizations, and they found no significant correlation of σ^{o} with wavelength. Their measurements were made over the range 10 to 50 Gc and for angles between 15° and 90°. Grant and Yaplee [1957] measured the sea over approximately the same angles and over the frequency range 9.4-35 Gc; their measurements were for transmission and reception of vertical polarization only. The measurements of Grant and Yaplee for various frequencies were not made simultaneously and, therefore, are presumably subject to wide variations due to differences in sea surface conditions. They reported that in general σ^{o} increases with frequency and was found to be 8 to 12 db greater at 35 Gc than at 9.4 Gc.

From the vastly different conclusions reached as a result of the two independent investigations (Wiltse, et al., and Grant and Yaplee), it might at first seem that an obvious difference in absolute values could be found by comparing data from the two investigations, and this in turn would help to pinpoint a possible calibration error. We have studied the data presented in the papers and have found no concrete suggestions regarding basic calibration difficulties. However, it is difficult to make meaningful comparisons of the data because detailed descriptions of the sea conditions under which the data were collected were not given. There is a tendency to favor the data given by Wiltse, et al., because values of σ^{o} were measured simultaneously for the different frequencies. However, the data given by Wiltse, et al., were collected on only three days, and it is risky to accept their conclusions because of the small amount of data and limited sea conditions investigated.

Long [1965] recently reviewed data contained in the appendix of Boring, et al. [1957] on radar cross section per unit area, σ^{o}, of the sea at 6.3 Gc and 35.0 Gc and for grazing angles between 1.5° and 4.0°. The data were obtained by simultaneously receiving both horizontally and vertically polarized echo components for transmitted polarizations which were sequentially changed between horizontal and vertical. Results indicate that sea echo is primarily caused by two scattering mechanisms: (1) a wind dependent fine structure of the sea (presumably ripples) that partly depolarizes and has a scattering cross section which depends on wavelength in accordance with λ^{-1}, and (2) gross structure of the sea (presumably smooth facets between the ripples) that does not depolarize and has a scattering cross section which is independent of wavelength. The cross sections for transmitting and receiving vertical polarization (σ^{o}_{VV}) and for transmitting and receiving horizontal polarization (σ^{o}_{HH}) are caused by the sum of the contributions from the two mechanisms. Therefore, although dependent on sea state and polarization, it seems that σ^{o}_{VV} and σ^{o}_{HH} will tend to be independent of wavelength at the lower frequency end of the microwave spectrum and will tend to depend on wavelength in accordance with λ^{-1} at the higher end of the spectrum. A comparison of data at 6.3 Gc and 35.0 Gc and for grazing angles between 1.5° and 4.0° indicates that the wavelength dependencies of σ^{o}_{VV} and σ^{o}_{HH} are functions of sea state but are greater than λ^{0} and are considerably less than λ^{-1}.

The fact that there is no apparent correlation of σ^{o} with wavelength in Figures 6, 7, and 8 suggests that σ^{o}_{VV} and σ^{o}_{HH} for the heavier seas change, at most, by several decibels throughout the microwave region. In other words, it appears that the spread in values of σ^{o} measured on different runs masks the differences caused by radar wavelength, per se. The magnitudes of the curves in Figure 11 are obtained from prediction equations resulting from a study of experimental data not included in Figures 6 and 7; the dependence of

σ^o on grazing angle was drawn to correspond roughly to match the data contained in Figures 6 and 7. The general agreement between Figure 11 with the experimental data of Figures 6 and 7 further suggests that the dependence of σ^o_{VV} on wavelength for the heavier seas is weak and is no larger than experimental errors and differences in σ^o caused by small changes in sea state.

With good reason, there is always doubt regarding the validity of comparisons of absolute radar cross section data for the sea. This is particularly true for σ^o_{HH} (Figure 8) because the available data for the plateau region are very scanty. However, it should be possible to gain some insight into the difference in wavelength dependence of σ^o_{VV} and of σ^o_{HH}. From data (Figure 9) on the relative magnitudes it has been found that σ^o_{VV} exceeds σ^o_{HH} even for grazing angles above the critical angle. The fact that X-band ratios are smaller than the corresponding L-band ratios suggests that σ^o_{HH} increases faster with a decrease in wavelength than does σ^o_{VV}. From the data reported by Macdonald for wind speeds of 11 to 22 mph, it appears that the ratio $\sigma^o_{VV}/\sigma^o_{HH}$ is at least 5 db greater at L-band than at X-band for grazing angles up to 20°; the data indicated that this difference in ratios diminishes for larger grazing angles.

Since σ^o_{VV} is not expected to increase with an increase in wavelength, the ratios for 11 to 22 mph suggest that σ^o_{HH} is at least 5 db less at L-band than at X-band for grazing angles up to 20°; the data also suggest that the difference in σ^o_{HH} at L-band and σ^o_{HH} at X-band diminishes for larger grazing angles.

E. Discussion

The various experimental measurements reported do not yield consistent agreement as to wavelength dependence of σ^o. This is partly because the measurements are complicated by the many environmental factors that affect the value of σ^o and which cannot be readily controlled. Further, in the low angle region where the interference effect is prominent, a λ^{-4} wavelength variation may be introduced, and this further complicates the analysis problem. However, in the plateau region (roughly 5° to 50° for microwaves) where the interference effect is minor, no clear correlation of σ^o with wavelength is apparent. Results of more recent experiments and opinions regarding these experiments indicate general agreement that within the plateau region the dependence on wavelength is between λ^{-1} and λ^0. The lack of a good correlation of σ^o measurements with wavelength can be accounted for by a number of factors: (1) the radar measurements required are extremely difficult; (2) the descriptions of the sea surface and other environmental conditions are inadequate and lack uniformity; (3) σ^o is highly sensitive to changes in environmental conditions (for example, wind speed) and can change quite rapidly; and (4) the dependence of σ^o on wavelength is apparently weak.

There are considerably more data for σ^o_{VV} than there are for σ^o_{HH}. From measurements on relative values for various polarizations, it has been found that σ^o_{VV} exceeds σ^o_{HH} even for grazing angles above the critical angle. Further, it has been observed that the ratio $\sigma^o_{VV}/\sigma^o_{HH}$ usually decreases for decreases in wavelength. These ratios, in combination with the fact that σ^o_{VV} is apparently a slowly varying function of wavelength, indicate, for grazing angles as large as 20°, that σ^o_{HH} may be as much as 5 db smaller at L-band than at X-band.

The wavelength dependence of σ^o is only one of several wavelength dependences which must be considered by a radar designer in choosing the best wavelength for a given application. Other characteristics of sea echo are affected by changes in wavelength, for example, short term amplitude and frequency distributions. The designer must also consider the wavelength dependence of target cross sections, atmospheric attenuation, clutter from rain and clouds, and so on. These questions as well as questions of available beamwidth, transmitter power, receiver noise figure, while crucial to the choice of a wavelength, are outside the scope of this investigation.

III. SEA ECHO FOR LOW FREQUENCIES

A. Introduction

The available data on sea echo at low frequencies are too limited to permit inductive reasoning to be applied to discover what patterns exist. It therefore became necessary to view these data in some other light. The procedure resorted to was to assume that the return possessed certain characteristics and then to compare these data to see if they supported the assumptions. The investigation does not lead to any definite conclusions, but the difficulty lies in the lack of data rather than in the procedure.

The characteristics which were assumed for sea return at the lower frequencies are those suggested by the microwave data. The microwave data which were reviewed in the preceding chapter are distributed over frequencies from L-band to about 35 Gc, a range of about 30 to 1. Since the characteristics of the sea return for rough seas did not seem to vary significantly over this wide frequency range, it seemed logical to assume that these same characteristics would hold at the lower frequencies. Briefly reviewing the characteristics discerned from the microwave data, we find that for horizontal polarization a graph of σ^o vs grazing angle shows three distinct regions, a region where σ^o is roughly proportional to θ^4 near grazing, a "plateau" region for the intermediate incidence angles, and a distinct rise near vertical incidence (see Figure 1). The angle separating the first two regions is called the critical angle, θ_c, and the angle separating the last two regions is designated θ_o.

The only definite frequency dependence appears to be associated with the interference effect, which determines the location of θ_c and makes σ^o a strong function of λ for all angles less than θ_c. For a given sea state, θ_c is proportional to the wave length. We therefore expect the curve of σ^o vs θ for the low frequencies to be similar to that for microwaves, except that the critical angle will be higher. The region of θ^4 dependence is thus elongated and the plateau region shortened. The curves for horizontal polarization might thus appear as in Figure 12. It is quite possible that at the lowest frequencies of interest, θ_c may increase to or near the angle θ_o and the plateau region disappear entirely, giving a curve similar to that shown in Figure 13.

For vertical polarization, the graph of σ^o vs θ is expected to resemble that for horizontal polarization in some respects, but to differ in other respects. They will be alike in that the graph for vertical polarization will also consist of three similar regions. It is expected that they will differ in three important respects: (1) σ^o_{VV} will be higher than σ^o_{HH} for most grazing angles, (2) the critical angle will not be proportional to wavelength, and (3) the functional dependence of σ^o on θ near grazing will not be proportional to θ^4. In order to present the basis for these statements, it is necessary that some additional consideration be given to the interference phenomenon which is inherent in all three statements.

B. The Role of Interference

As discussed briefly in Section I the θ^4 dependence of σ^o at low grazing angles for horizontal polarization is due to interference. For microwave frequencies it is likely that this statement is approximately true for vertical as well as for horizontal polarization although there is insufficient low angle data for vertical polarization to permit a definite conclusion to be drawn.

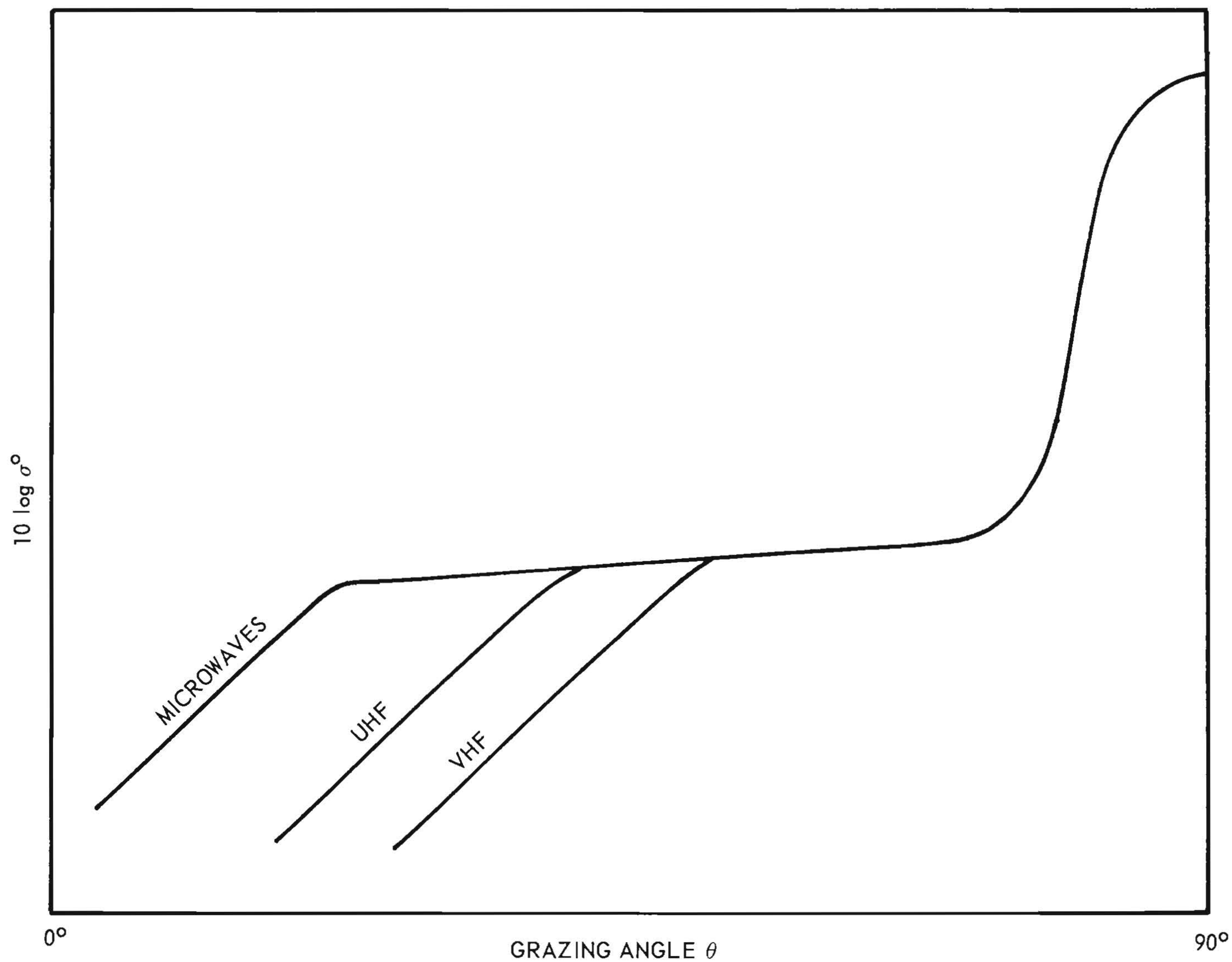

Figure 12. Assumed Shape of σ^0 Versus Θ Curves for Horizontal Polarization.

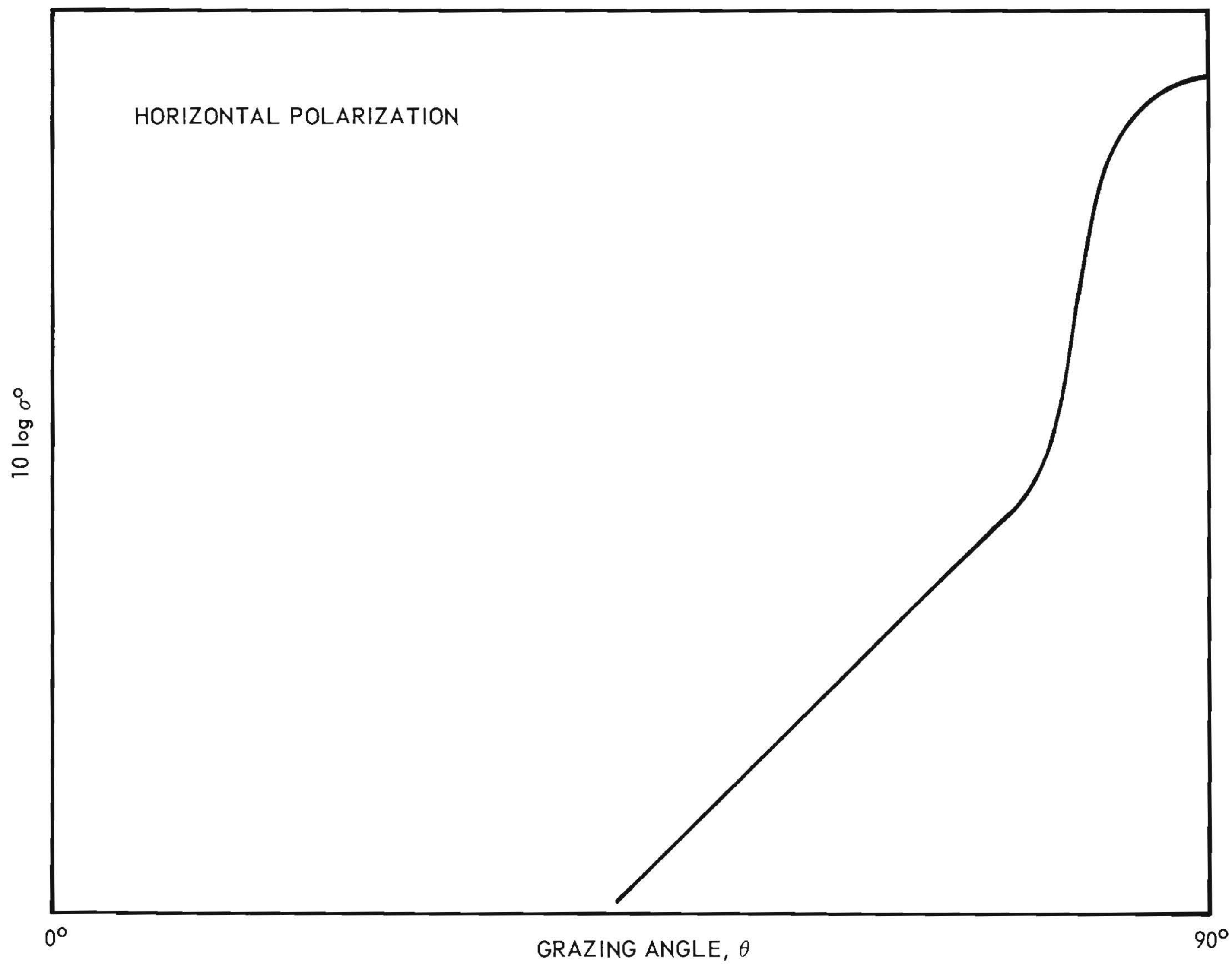

Figure 13. Assumed Shape of σ^O Versus Θ Curve for Low Frequencies such that $\Theta_c \geq \Theta_o$.

However, for the lower frequencies, the statement is strictly true only for horizontal polarization.

For horizontal polarization, the reflection coefficient has a magnitude of essentially one and a phase shift of 180° for all angles of incidence. Thus the vertical field pattern of an overwater area illuminated with horizontal polarization always shows sharp nulls with the lowest null at the surface. Katzin has shown [Povejsil, et al. 1961, p. 213] that when the height of the surface irregularities is approximately equal to the height of the first lobe maximum, decreasing the grazing angle will cause σ^O to decrease as θ^4. Thus the critical angle, θ_c, for horizontal polarization is that grazing angle which positions the height of first maximum at approximately the height of the surface irregularities. Since the lobe spacing varies as $\lambda/\sin\theta$, it follows that doubling the wavelength and the angle will give approximately the same field pattern. Thus the critical angle increases approximately linearly with λ.

For vertical polarization, the situation is quite different. Both the magnitude, ρ, and phase, ϕ, of the reflection coefficient vary with both grazing angle and frequency. The angle for which ϕ is 90° (and ρ a minimum) is known as Brewster's angle. At grazing angles less than Brewster's angle, the phase shift exceeds 90°, while at higher grazing angles the phase shift is less than 90°. Thus destructive interference can occur near the surface only when the grazing angle is below Brewster's angle; in order for the interference to be appreciable, the grazing angle must be well below Brewster's angle. We would therefore expect to find the knee of the σ^O curve (critical angle) connecting the plateau region with the rapid drop near grazing to be well below Brewster's angle. This fact has little bearing on the σ^o plot for microwave frequencies. For instance, at X-band Brewster's angle is about 8°, whereas θ_c is usually below 1°. At 1° the reflection coefficient does not differ greatly from unity with a phase shift of very nearly 180°. Therefore as the grazing angle is decreased, we expect destructive interference to begin occurring on both vertical and horizontal polarizations at almost the same (critical) angle.

At the lower frequencies, the situation is quite different. θ_c may be as high as 4° for horizontal polarization at 1,000 Mc (even higher for lower frequencies), while Brewster's angle has decreased to approximately 2°. As the frequency is lowered further, θ_c for horizontal polarization increases to still larger angles while Brewster's angle will decrease.

In summary, for the low frequencies and vertical polarization, as the grazing angle is decreased destructive interference will not be expected until the grazing angle becomes very small (of the order of 1° or less). Therefore it is expected that the plateau region of the σ^o curve will extend to much lower angles than that for horizontal polarization. Furthermore this "critical angle" for low frequency and vertical polarization will be largely independent of the surface irregularities. It will be determined almost entirely by the frequency. Also, below this critical angle the decrease of σ^o with θ may reach a rate much greater than θ^4, since decreasing θ "sharpens" the interference pattern in addition to moving the lower lobe higher in space. As the grazing angle approaches zero, σ^o_{VV} should approach σ^o_{HH} since the vertical reflection coefficient approaches unity at a phase shift of 180°. We thus expect the general shape of the σ^o vs θ curves for the lower frequencies to be as shown in Figure 14. Unfortunately the available data are insufficient to validate

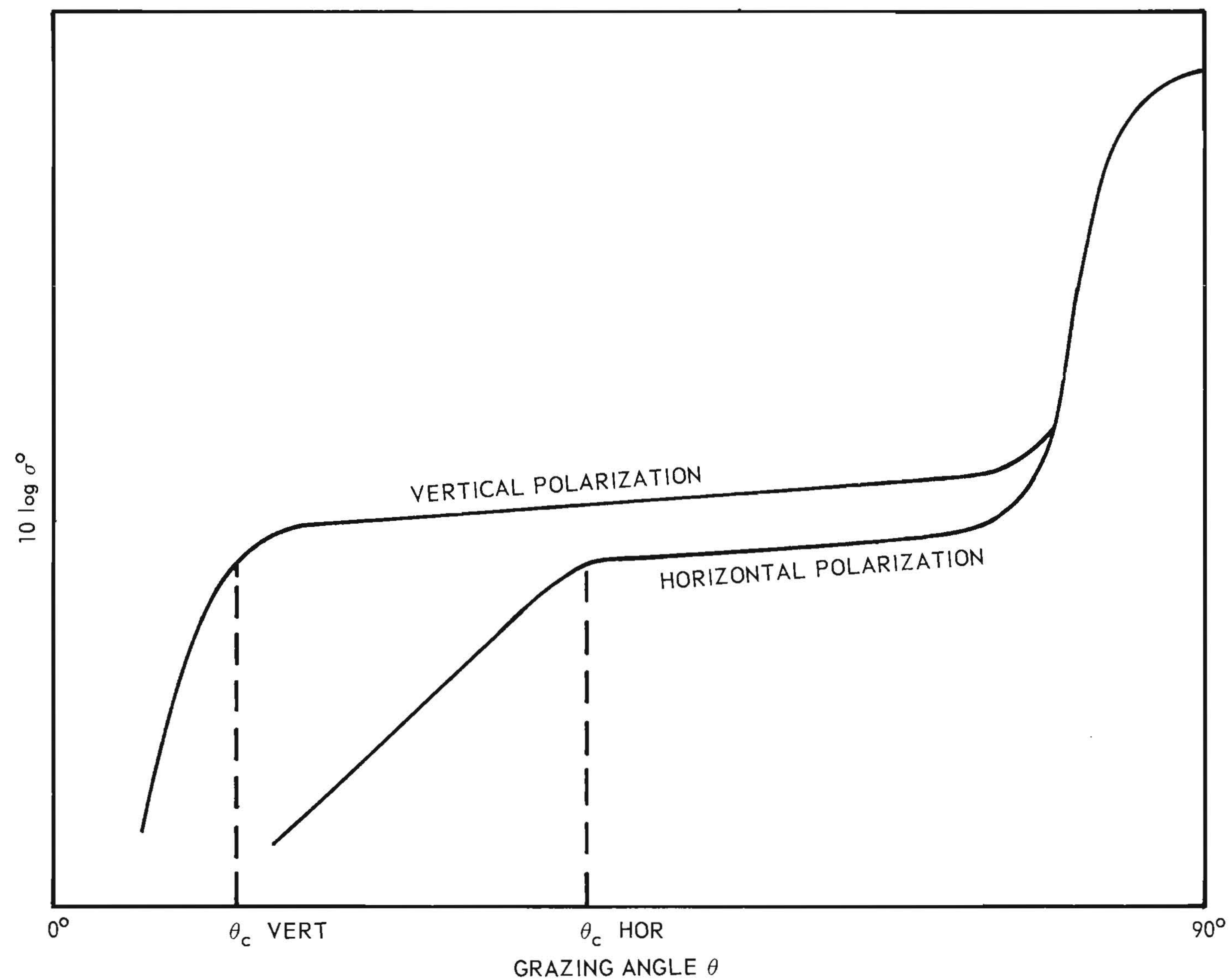

Figure 14. Appearance of σ^{O} Versus Θ Curves for UHF.

these assumptions completely. Those which are available do agree to a large extent with these concepts, although one set of data indicated somewhat different dependence on λ and θ for low grazing angles, as discussed below.

C. Measurements

Ingalls and Stone [1956] studied the characteristics of sea clutter at 18.39 Mc and 24.70 Mc for vertical polarization. The antenna was positioned about 50 feet above the surface, and the propagation was by ground wave. Sea clutter was measurable to ranges of 100 miles.

Although the object of their study was not to measure σ^O, they report at 18.39 Mc that "the effective radar cross section is in the order of 5×10^{-4} square meters per square meter of sea area." Expressed in decibels, this figure would be -33 db which agrees quite well with the return that would be expected in the plateau region.

NRL personnel [Ament, et al., 1958] studied sea return at low grazing angles at 220 Mc and horizontal polarization. The radar, which was blimp mounted, radiated a 5 μsec pulse at a prf of 300. The antenna was rigidly mounted and the return from different depression angles was separated by range gating. The maximum grazing angle for which data were recorded was about 14°.

The data are shown in three graphs, each displaying the data recorded during one day. The graphs show received power as a function of grazing angle along with a line representing the -80 db level for σ^O. From these graphs the values of σ^O can be determined. They cluster very tightly around a θ^4 variation line and reach a maximum value of about -38 db at 14° grazing. This result is in agreement with expectations, since for 220 Mc and horizontal polarization, it is expected that the critical angle will be large (of the order of 20° to 30° for moderate seas). Therefore the grazing angles for which data were recorded, 0° to 14°, all lie in the near-grazing angle region and a θ^4 variation would be expected.

Although the graphs also indicate whether each data point represents an upwind, downwind, or crosswind measurement, no definite dependency of σ^o on wind direction is discernible from these data. Note that this result differs from that obtained from microwave data.

Curry [1965] reports measurements of sea clutter made with the Tradex radar system. The Tradex system is a large pulse compression system that operates on two frequencies (425 and 1320 Mc) simultaneously. Transmitted signals are right circularly polarized and both circular polarizations are monitored on reception. The large, narrow-beam antenna is positioned at a fixed height above the surface which gives a radio horizon of 13 nautical miles.

Measured values of σ^o are reported at ranges of 7.5, 10, 12.5, and 15 nautical miles. From the geometry, the grazing angle for the shortest range was calculated to be about 4 minutes of arc. The next two ranges have even lower grazing angles, while the longest range is for beyond-the-horizon propagation.

The measured values of σ^o scatter from -90 db to -110 db, for all ranges and both frequencies. The scatter is such that there is no discernible pattern in the level of σ^o as a function of ranges (grazing angle) or as a function of frequency. Also no significant difference is evident in the return observed in the right and left circularly polarized channels.

The relatively few data points (2 to 4 data points at each frequency are reported for each range) suggest no pattern to the return other than the fact that σ^{O} is quite small. Since it is expected that the magnitude of σ^{O} as observed on circular polarization will be no smaller than 6 db below the return for vertical polarization, these data support the belief that σ^{O} for vertical polarization drops markedly as the grazing angle decreases to values near zero.

A group at Stanford Research Institute [Nielson, et al., 1960; Hagn, 1962] measured sea clutter at 32.8 Mc on both horizontal and vertical polarization. The equipment was mounted on an airplane and the data were recorded while in flight. Separate fixed horizontal and vertical antennas were used and the return from various grazing angles separated by range gating. For sea return measurements, only two runs on horizontal polarization and only one run on vertical polarization are reported. The grazing angles spanned a range of about 10° to 60° on each run.

At first glance, these data were disturbing in that they did not conform to expectations. Further, it is risky to accept their results because of the small amount of data and the limited sea conditions investigated.

The reported values of σ^{O} for vertical polarization were almost constant over the entire range of grazing angles, with an average value of about -40 db. The return for horizontal polarization shows a decided increase with grazing angle. At the lowest grazing angles (about 10°), σ^{O} was in the neighborhood of -43 db; it increased to about -5 db at the highest grazing angle (near 60°). From 10° to about 40° the increase corresponds closely to a θ^{4} variation (it seems reasonable that at this low frequency and horizontal polarization, interference effects should be prominent and the critical angle should be very large); above 40°, the increase is even more rapid, which is difficult to explain. Also the return for horizontal polarization is greater than that for vertical polarization for all except the lowest grazing angles; this is contrary to what would be expected; therefore, the return for horizontal polarization appears to be much too high and increasing too fast with grazing angle.

Hagn was aware that some apparent discrepancy existed when his 1962 report was published. His discussion of the data [Hagn, 1962, p. B-121] includes the statement, "log comments indicate that vertical polarization yielded the stronger echoes, hinting that there might be a calibration error." In further discussion Hagn estimates that the error might be as large as 10 db.

Another observation of these data is perhaps worth mentioning. On page A-7, Hagn [1962] cites the equation for reducing the raw data to values of ρ in the form of

$$\rho(\Delta) = \frac{\text{Power Received}}{G_T G_R} f(P_T, h, \lambda, t, \tau) \quad .$$

Since the same antenna was used for transmitting and receiving, $G_T = G_R$ and the denominator is simply G^2. A table of G^2 is given on page 2 of Hagn's report. We noted that when the function k/G^2 was plotted, k being a constant suitably determined, the function corresponded very closely to the points plotted for $\rho(\Delta)$ for horizontal polarization. It follows that the measured values of received power must have been about the same for every grazing angle. This could be a coincidence, but it suggests the possibility of a malfunctioning receiver.

Finally, a problem may exist in making measurements of σ^o for horizontal polarization at low frequencies due to possible "contamination" from vertically polarized return. This problem was mentioned by Hagn on page A-5 of his [1962] report. The contamination is introduced by the requirement that the electric field be both in the plane of the exciting dipole and orthogonal to the direction of propagation. This problem does not arise for vertical polarization, but for a horizontally polarized dipole suspended above the sea surface, the radiation striking the surface is truly horizontally polarized only for the azimuths which are perpendicular to the dipole. For radiation at other azimuths, the electric vector at the sea surface will be slanted and can be broken into horizontal and vertical components. The amount of contamination is a function of both the depression (or grazing) angle and the azimuth angle measured with respect to the main beam axis. For small azimuth angles, say 5° or 10° off the axis, the contamination is negligible for all depression angles; consequently, this problem is negligible in microwave measurements where narrow-beam antennas are used.

For the low frequencies, however, the effect can present a serious problem. Low frequency antennas are usually broad-beamed, particularly for airborne antennas which are subject to size and weight limitations. For typical low-frequency antenna patterns, radiation and detection of the vertical component may produce power levels close to those due to the horizontal component. This effect could cause errors in the measurement of σ^{o} for horizontal polarization, particularly if, as suspected, σ^{o} for vertical polarization is greater than σ^{o} for horizontal.

We did not study the contamination problem as applied to the SRI data in any great depth, since these data were dropped for the reasons previously discussed. However, anyone contemplating low-frequency measurements of sea return should be aware of the problem when designing experiments.

The largest set of data on low frequency sea return was collected by Lincoln Laboratories in connection with airborne radar tests [Freedman, et al., 1954]. Measurements were made at both 10 cm and 70 cm wavelengths (2880 Mc and 428 Mc) for horizontal polarization. The 70 cm UHF equipment was mounted in a blimp. A number of runs were made with some variations in the altitude of the blimp, but most of the data were collected while flying at an altitude of 3000 feet. The sea return data were confined to the smaller grazing angles, the upper limit being approximately 6° for most of the runs.

Although these data do not cover the grazing angles of primary interest (the plateau region), they represent the most extensive data collected at low frequencies. The results are of interest particularly since they indicate some possible variations from the assumed characteristics of the σ^{o} curves at the low grazing angles that were stated earlier in this chapter.

The sea states existing during the runs were classified as either "calm" or "rough", and data collected for each of these states were quite consistent from run to run. The return at S-band (10 cm) was generally higher than the return at UHF, although cases were observed where the UHF return was higher for calm seas. The return at both frequencies increased with increasing roughness of the sea, but the S-band return increased much more than the UHF return. For the rough sea condition, comparison of the data at the two frequencies shows that the wavelength dependence is close to that assumed in this region, namely λ^{-4}. The dependence on grazing angle, however, was measured to be closer to θ^3 rather than θ^4. For calm sea conditions, grazing angle dependence was still of the order of θ^3, but wavelength dependence was greatly diminished, being less than λ^{-1}.

Graphs of the individual run data are given in Freedman, et al. [1954], along with graphs of averaged data for each of the two sea conditions. These averaged data show that for a 1° grazing angle and 70 cm wavelength, σ^o is about -79 db for calm seas and about -68 db for rough seas. Corresponding values for the 10 cm wavelength are about -71 db and -38 db. From the averaged data, empirical curves were constructed. These give σ^o for calm sea conditions to be

$$\sigma^o{}_{calm} = 10^{-1.32} \frac{\theta^{2.98}}{\lambda^{0.66}}$$

and for rough sea conditions

$$\sigma^o{}_{rough} = 10^{5.54} \frac{\theta^{2.66}}{\lambda^{4.27}}$$

where θ is in radians and λ in centimeters.

These data gave no definite indication of a critical angle existing within the range of grazing angles measured.

The main point of disagreement between these data and the assumed nature of the return lies in the diminished wavelength dependence for calm seas. One plausible explanation of this might be that all sea states observed appeared essentially smooth to the 70 cm radiation, while varying from smooth to rough for the 10 cm radiation.

D. Conclusions

The main conclusion drawn from reviewing the low frequency data is that these data are insufficient to determine the character of σ^o at low frequencies with any degree of certainty. Those data which are available tend to support the assumption that σ^o for low frequencies is basically similar to σ^o for microwave frequencies except for the following:

(1) For horizontal polarization the critical angle θ_c will be higher at low frequencies than it is for microwaves. For a given sea state, θ_c should vary such that sin θ_c is proportional to λ.

(2) For the low grazing angles below θ_c (interference region), the Lincoln Labs data [Freedman, et al., 1954] indicate that the dependence of σ^o on θ is approximately θ^3 rather than θ^4. Although this finding was quite consistent over many runs, it is at variance with NRL's [Ament, et al., 1958] data which indicate a θ^4 dependence quite precisely. It can be concluded, then, that for the low grazing angles, the dependence is somewhere between about θ^3 and θ^4.

(3) It is expected that at the low frequencies and for vertical polarization, the critical angle will be of the order of 1° or less, while for horizontal polarization the critical angle will be larger. Attaching values to the critical angle for horizontal polarization is difficult. A critical angle of about 3° to 4° was observed at 430 Mc [Durlach, 1965] while measurements at 220 Mc showed a near-perfect θ^4 variation for grazing angles up to 14°, indicating that the critical angle was greater than 14° [Ament, et al., 1958]. Thus the critical angle for horizontal polarization is not determined by wavelength alone, but probably depends heavily on sea state. On the other hand it is expected that the value of the critical angle for vertical polarization will be a function of wavelength only, not of sea state. There are no data to test this assumption.

(4) There are no reliable data on low frequency sea echo at grazing angles in the plateau region.

IV. CURRENT MEASUREMENTS PROGRAMS

The authors know of only one active program which is directly concerned with wavelength dependence of sea echo. The program is a cooperative effort between Johns Hopkins Applied Physics Laboratory, with funding from the Bureau of Naval Weapons, and the Naval Research Laboratory. Mr. Frank C. Macdonald (Naval Research Laboratory) is supervising the radar measurements and Mr. Isadore Katz (Applied Physics Laboratory) is supervising the effort to obtain detailed optical descriptions of the sea. Both Katz and Macdonald are intimately connected with interpreting the radar data and correlating the results with the optical descriptions of the sea surface.

Echoes from terrain, sea, and ships are to be measured with a sophisticated airborne four-frequency radar system having a 20-to-1 range of frequencies. The system is phase coherent, is designed to measure the polarization matrix, has built-in calibration techniques and tape recording of data, features a common antenna whose depression angle can be varied from horizontal to straight down, has range accuracy of several yards out to 200 miles, and has double recording gates for targets and clutter. The principal components of the system are four pulsed coherent radars transmitting at P-band (428 mc), L-band (1225 mc), C-band (4455 mc), and X-band (8910 mc), each designed to operate horizontally or vertically polarized, either separately or pulsed alternately. The system is designed so that four frequencies can be transmitted singly or in rapid succession to provide a total of eight different vertically and horizontally polarized transmissions. System calibration is accomplished by dropping aluminum spheres from the aircraft and measuring their echoes while manually tracking them up to 2 to 3 miles behind the aircraft.

The present status of the program is that all equipment except the two low frequency transmitters have been installed in a WV-2 aircraft, and a few measurements of sea clutter have already been made at C-band and X-band at grazing angles of 5°, 10°, 15°, 30°, 60°, and 90° with both horizontally and vertically polarized radiation. These measurements were made in December, 1964, and are presently being analyzed. The schedule of these experiments calls for the measurement of sea clutter, on four frequencies at all angles, both polarizations, and a number of sea state conditions in the period June to August 1965. This program is coordinated with a program to measure the fine-scale contour of the sea by stereo photography with a wave height accuracy of 0.03 inch.

Given adequate time, this program can provide much needed information on sea echo. However, accurate answers to the questions being examined in these experiments are extremely difficult to obtain. It must be stressed that only through a continuous program of measurements and analyses extending over many months, and possibly years, will it be possible to obtain all of the desired results.

V. CONCLUSIONS

A review of the literature on sea echo measurements has been made to determine the wavelength dependence of radar cross section per unit area, σ^o, for frequencies from a few tens of megacycles to a few tens of gigacycles. Although there is an enormous body of literature on sea echo, much of it expresses seemingly conflicting views about various attributes of sea echo. Among the attributes in question is the functional dependence of sea echo on wavelength.

There are several reasons for these apparent conflicts. First, the required measurements are among the most difficult to make, and the uncertainties in measurements, the large variability of possible sea conditions, and the wide choice of available radar parameters cause variations from measurement to measurement which are difficult to correlate. Second, the wavelength dependence of sea echo is not a simple functional relationship which is independent of other parameters. In particular, the dependence varies with grazing angle, polarization, and sea state. Finally, the problem is further complicated by the fact that the magnitude of σ^o is also dependent on these same parameters. For example, for fixed wavelength, σ^o varies with grazing angle; for fixed grazing angle, σ^o varies (usually) with wavelength. The variation for two different grazing angles is different, however. Similarly, both the wavelength dependence of σ^o and the magnitude of σ^o varies with polarization and sea surface conditions. These inter-relationships make the subject difficult to discuss in addition to complicating the analysis. It is necessary that all pertinent parameters be stated before any statement relative to wavelength dependence is made.

The analysis was further complicated by the non-uniformity in the distribution of data with respect to radar parameters. Most of the data available are for transmitting or receiving either horizontal or vertical polarization; little data were available for circular polarization. For frequencies in the microwave region, there are fewer data available for horizontal polarization than for vertical. For the lower frequencies, there are few data for horizontal polarization and even less for vertical polarization. In fact, the main conclusion drawn from reviewing the data for frequencies below 220 megacycles is that these data are insufficient to determine the character of σ^{o} with any degree of certainty. Furthermore, the data for frequencies below 1000 megacycles are insufficient to make any reliable estimates for grazing angles larger than the critical angle. It should be borne in mind that all of the following conclusions except those for small grazing angles apply only for frequencies in the microwave region. The conclusions relative to the small grazing angles also apply to the lower frequencies (220 megacycles and up) for horizontal polarization.

Since little data are available for circular polarization, a method for relating σ^{o} for circular polarization to those for horizontal and vertical polarizations is given. It is well known that for certain applications the use of circular polarization will provide substantial improvement in target echo relative to cloud and rain clutter; the investigation indicates that no substantial reduction of sea echo is to be expected.

One of the easiest parameters to deal with is grazing angle. The range of possible grazing angles can be divided into three fairly distinct regions: "near grazing incidence," the "plateau region," and "near vertical incidence." Within each of these regions, the dependence of σ^{o} on grazing angle, and the dependence of σ^{o} on wavelength can be characterized to some extent. However, the boundaries of the three regions change with wavelength, sea surface condition, and polarization.

The behavior of sea echo in the near grazing incidence region is generally accounted for on the basis of destructive interference between the direct and reflected radiation which illuminate the scatterers. The upper angular limit of this region, the so-called "critical angle" separating the near grazing and plateau regions, is that angle at which destructive interference ceases to be a dominant factor. Thus the position of the critical angle depends on several factors. Since the effect of destructive interference is more pronounced for transmitting and receiving horizontal polarization, the critical angle can be different for horizontal and vertical polarizations. The critical angle tends to decrease as the roughness of the sea increases; also, the critical angle is larger for longer wavelengths. For example, at X-band, the critical angle has been found to be in the range of 1/4° to 3/4°; at 70 cm, the critical angle has been reported to be between 3° and 4°; and at 220 megacycles the critical angle has been found to be larger than 14°.

Confining our attention to the small grazing angles within the near grazing incidence region, the following statements can be made:

1. Based on the interference model, the magnitude of σ^{o} is expected to increase rapidly (approximately as θ^{4}) with increases in grazing angle. Most of the data for small grazing angles support this statement.

2. Wavelength dependence is quite strong and σ^{o} can vary as rapidly as λ^{-4}.

3. From measurements on relative values for various polarizations, σ^{o}_{VV} is usually substantially larger than σ^{o}_{HH} for calm to moderate

seas, occasionally by more than 20 db for microwaves. For rougher seas, the two cross sections are more nearly equal. Under these conditions σ^o_{VV} is still slightly larger than σ^o_{HH} most of the time, but cases have been reported where σ^o_{HH} was observed to exceed σ^o_{VV}. For grazing angles in the plateau region, the following statements hold:

1. The magnitudes of σ^o_{VV} and σ^o_{HH} for a 5° grazing angle are expected to be in excess of -30 to -35 db 50 per cent of the time for microwaves.
2. The magnitude of σ^o varies only slightly with grazing angle. Microwave data indicate an increase of about 1/4 db per degree increase in grazing angle.
3. The wavelength dependence of σ^o appears to be so weak that it is largely masked by the uncertainties in measurement and the strong sensitivity of σ^o to uncontrollable environmental conditions. Nevertheless, present data on σ^o_{VV} (there are considerably more data for σ^o_{VV} than for σ^o_{HH}) indicate that σ^o_{VV} increases slightly for a decrease in wavelength.
4. σ^o_{VV} is usually larger than σ^o_{HH}.
5. It has been observed that the ratio $\sigma^o_{VV}/\sigma^o_{HH}$ usually decreases for decreases in wavelength. This fact, in combination with the fact that σ^o_{VV} increases slightly for a decrease in wavelength, suggests that σ^o_{HH} is more dependent on wavelength than is σ^o_{VV}. Values of the ratio $\sigma^o_{VV}/\sigma^o_{HH}$ measured at X-band and at L-band suggest that σ^o_{HH} may be as much as 5 db smaller at L-band than at X-band for moderate sea conditions and a grazing angle of 20°.

The grazing angles near vertical incidence were not of primary interest in this study, and conclusions for this region are meager. Nevertheless, the following statements can be made about the region near vertical incidence:

1. Generally σ^o tends to decrease as the surface roughness increases.
2. The wavelength dependence for frequencies in the microwave range seems weak, if indeed there is any dependence at all.
3. It is not possible to assess the dependence of σ^o on wavelength for frequencies below the microwave range due to a lack of data. Theoretically for rough seas and vertical incidence, one would expect σ^o to increase with an increase in λ. This behavior is expected because a sea which would appear rough at microwave frequencies could appear mirror-smooth to a radar whose wavelength is larger than the irregularities in the sea surface.

VI. RECOMMENDATIONS

Advanced system design programs are always in need of more refined sea echo data, but these data cannot be obtained in the few months that are usually allotted for acquiring them. It takes years to develop a competent measurement and analysis team and sometimes years to complete an experiment. Therefore, orderly funding should be provided to help nurture productive teams that now exist.

Sea echo data are needed for frequencies extending from the VHF region through the millimeter wavelength region. Measurements on σ^{o} should be taken simultaneously at widely separated wavelengths and over a wide range of grazing angles and sea conditions. Although data are needed for all polarizations, fewer data have been published for σ^{o}_{HH}. Even with carefully designed experiments and equipment, it is likely that the probable errors in the relative values of σ^{o} measured at two wavelengths will be as much as 3 db. Therefore, since the dependence of σ^{o} on wavelength is expected to be small for all but small grazing angles, operating wavelengths should be chosen so that there is at the very least a 10-to-1 range of wavelengths available for each experiment.

Very little data for σ^{o} exist for frequencies in the region of a few tens of megacycles to a few hundred megacycles. To obtain valid data for horizontal polarization, care must be taken to make sure that effects of polarization "contamination" caused by broad beamed antennas is negligible. Initial measurements should be made with a ground-based radar so that a reasonably narrow-beam antenna can be used.

In addition to data on average values of σ^{o}, detailed data on its short-term variations are needed. The relationship of both the amplitude distribution of σ^{o} and the distribution of fluctuation frequencies to such variables as wavelength, other radar parameters, and sea state should be investigated. For certain applications, information on the dependences of amplitude and fluctuation frequency distributions on wavelength may be more important than information on wavelength dependence of σ^{o}.

Radar researchers need to use a set of standardized descriptors of the sea surface so that in the future more meaningful correlations can be made between the results of various investigations. It is recommended that, at the very least, investigators report wind speed, wind direction, wave height, wave direction, and clear statements as to how these quantities were obtained.

More interaction is needed between research teams and radar designers. It is recommended that consideration be given to the establishment of an information analysis center on sea echo. Such a group could assist qualified users by providing specialized advisory services as well as routine summaries and state-of-the-art analyses. As envisioned, the center would gather, analyze, evaluate, condense, and disseminate information pertinent to sea echo.

It will take years to get the answers on sea clutter that are currently needed. To keep pace with the increasing requirements for more refined data, several programs are needed that operate on a continuous and long-term basis.

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Respectfully submitted,

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Appendix

DERIVATIONS FOR CIRCULAR POLARIZATION

There are considerably less published data on sea echo for circular polarization than for linear polarization. This appendix is concerned with equations which are useful for predicting the magnitude of circularly polarized echoes from results obtained for horizontal and vertical polarizations.

The concepts of electromagnetic polarization are covered in the standard references [Kraus, 1950; Stratton, 1941], and much of the theoretical background was developed in studies of polarized light. Chandrasekhar [1950], who was primarily interested in scattering in stellar and planetary atmospheres, thoroughly described the concept of scattering of light by matrix analysis. Also, numerous papers [Sinclair, 1948; Kennaugh, 1952; Graves, 1956; Copeland, 1960; Olin and Queen, 1961] have been published on the polarization characteristics of radar echoes.

In general, the polarization of the electromagnetic wave can be characterized by a vector. This vector consists of two orthogonal components which can be linear, circular, or elliptical. The change in polarization due to reflection from a target can be considered as a change in the components of the vector representing the wave falling on the target. The new components are obtained by multiplying the incident wave vector by a matrix representing the target properties. The new vector then represents the reflected wave. In the case of a linear reference system, the relationship, suppressing range dependence, between the incident and reflected vectors and the transforming matrix may be given as follows:

$$\begin{pmatrix} E_x^r \\ \\ E_y^r \end{pmatrix} = \begin{pmatrix} a_{xx} & a_{yx} \\ \\ a_{xy} & a_{yy} \end{pmatrix} \begin{pmatrix} E_x^t \\ \\ E_y^t \end{pmatrix} . \tag{1}$$

For the circular reference systems:

$$\begin{pmatrix} E_1^r \\ \\ E_2^r \end{pmatrix} = \begin{pmatrix} c_{11} & c_{21} \\ \\ c_{12} & c_{22} \end{pmatrix} \begin{pmatrix} E_1^t \\ \\ E_1^t \end{pmatrix} . \tag{2}$$

E_x and E_y, and E_1 and E_2 are orthogonal linear and circular components, respectively, of the electric vector lying in the plane perpendicular to the direction of propagation, and the superscripts $\underline{t}$ and $\underline{r}$ indicate transmitted and reflected components. Elements a_{ij} and c_{ij} are in general complex (phase factors). The first subscript designates transmitted polarization and the second designates reflected polarization. For most cases, the square matrices are symmetric, i.e., $a_{ij} = a_{ji}$ and $c_{ij} = c_{ji}$. For the derivations that follow, it is assumed that $a_{ij} = a_{ji}$ and $c_{ij} = c_{ji}$.

The matrix coefficients a_{ij} and c_{ij} in Equations 1 and 2 can be expressed in terms of one another by expressing E_1^t and E_2^t in terms of E_x^t and E_y^t. The assumption is made that $E_y^t = j\, E_x^t$, that is, the transmitted wave may be described as the sum of two linearly polarized waves that are perpendicular in space and are in phase quadrature. Such a wave is circularly polarized and the rotating electric field of this wave will be called E_1^t. It may be readily seen that $|E_1^t| = \sqrt{2}\, |E_x|$. If E_y^t were equal to $-j\, E_x$, the transmitted wave would also be circularly polarized, but the direction of rotation of the electric field would be opposite to that of E_1^t; therefore, by definition E_1^t would be zero. The rotating electric field for the case that E_y^t is equal to $-j\, E_x^t$ is defined herein as E_2^t. In summary, E_1^t is defined as the circularly polarized electric field that exists if $E_y = j\, E_x$ (for this case E_2^t is zero), and E_2^t is defined as the circularly polarized electric field that exists if $E_y = -j\, E_x$ (for this case E_1^t is zero).

From Equation 1 and the definitions above, if $E_y^t = j\, E_x^t$ (that is, $E_2^t = 0$)

$$E_x^r = \frac{|E_1^t|}{\sqrt{2}} [a_{xx} + j\, a_{xy}] \text{ and } E_y^r = \frac{|E_1^t|}{\sqrt{2}} [a_{xy} + j\, a_{yy}] \quad . \tag{3}$$

Similarly, if $E_y^t = -j\, E_x^t$ (that is, $E_1^t = 0$)

$$E_x^r = \frac{|E_2^t|}{\sqrt{2}} [a_{xx} - j\, a_{xy}] \text{ and } E_y^r = \frac{|E_2^t|}{\sqrt{2}} [a_{xy} - j\, a_{yy}] \quad . \tag{4}$$

On reception, the outputs of antennas that radiate circularly polarized fields E_1^t and E_2^t are proportional to E_1^r and E_2^r, respectively. E_1^r and E_2^r, in terms of linearly polarized components, are:

$$E_1^r = \frac{E_x^r + j\, E_y^r}{\sqrt{2}} \text{ and } E_2^r = \frac{E_x^r - j\, E_y^r}{\sqrt{2}} \quad .$$

From Equation 2, it may be seen that

$$|c_{11}| = \left|\frac{E_1^r}{E_1^t}\right| \text{ if } E_2^t = 0,$$

and

$$|c_{22}| = \left|\frac{E_2^r}{E_2^t}\right| \text{ and } |c_{12}| = \left|\frac{E_1^r}{E_2^t}\right| \text{ if } E_1^t = 0 \quad . \tag{5}$$

Therefore, the matrix elements c_{ij} may be obtained by using Equation 5 with the received fields from Equations 3 and 4. The results are

$$|c_{11}| = \left|\frac{a_{xx} - a_{yy}}{2} + ja_{xy}\right| \quad ,$$

$$|c_{12}| = \left|\frac{a_{xx} + a_{yy}}{2}\right| \quad ,$$

and

$$|c_{22}| = \left|\frac{a_{xx} - a_{yy}}{2} - ja_{xy}\right| \quad . \tag{6}$$

The x and y directions applicable to Equations 6 are arbitrary. To discuss data for horizontal and vertical polarizations, assume that the x and y directions point to the right and upward, respectively. Then, the definitions of E_1^t and E_2^t result in directions 1 and 2 being left circular and right circular, respectively. For most purposes, circularly polarized echoes are described simply as "same" and "opposite"; this means that the echo is rotating in either the same or opposite direction as is the transmitted wave.

As previously stated, the a's and c's are complex quantities (contain phase information) that are proportional to the electric fields. To equate the various radar cross sections (proportional to electric field squares), care must be taken to appropriately account for phase. Considered below are three limiting cases for transmitting and receiving the same polarization.

Case I

Assume that a_{xx} is equal to a_{yy}. This means it is assumed that at all times the phase change and amplitude upon reflection is the same for both polarizations. Then it may be seen that

$$|c_{11}|^2 = |c_{22}|^2 = |a_{xy}|^2 \quad ,$$

and

$$|c_{12}|^2 = |a_{xx}|^2 = |a_{yy}|^2 \quad .$$

Thus, if a_{xx} is, on an instantaneous basis, equal to a_{yy}

$$\sigma_{11} = \sigma_{22} = \sigma_{xy}$$

and

$$\sigma_{12} = \sigma_{xx} = \sigma_{yy} \quad .$$

Case II

Assume that a_{xx}, a_{yy}, and a_{xy} are incoherent in the sense that the relative phases between the quantities are random. Then, on the average, it is expected that

$$|c_{11}|^2 = |c_{22}|^2 = \frac{|a_{xx}|^2}{4} + \frac{|a_{yy}|^2}{4} + |a_{xy}|^2$$

and

$$|c_{12}|^2 = \frac{|a_{xx}|^2}{4} + \frac{|a_{yy}|^2}{4}$$

or

$$\sigma_{11} = \sigma_{22} = \frac{\sigma_{xx}}{4} + \frac{\sigma_{yy}}{4} + \sigma_{xy}$$

and

$$\sigma_{12} = \frac{\sigma_{xx}}{4} + \frac{\sigma_{yy}}{4} \quad .$$

<u>Case III</u>

Assume that a_{yy} is much greater than a_{xx} and a_{xy}. Then, it may be seen that

$$|c_{11}|^2 = |c_{12}|^2 = |c_{22}|^2 = |a_{yy}|^2/4 \quad .$$

Thus, for this case, the various cross sections for circular polarization would be equal and would be greater than σ_{xx} but 6 db less than σ_{yy}.

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13. ABSTRACT

A review of the literature on sea echo measurements has been made for frequencies from a few tens of megacycles to a few tens of gigacycles. Effects of changes in wavelength, angle of incidence, polarization, and sea condition on σ^o, radar cross section per unit area of the sea, are discussed. For microwave frequencies, the range of possible grazing angles can be divided into three fairly distinct regions: "near grazing incidence," the "plateau region," and "near vertical incidence." Within each of these regions, the dependence of σ^o on grazing angle, and the dependence of σ^o on wavelength can be characterized to some extent. However, the boundaries of the three regions change with wavelength, sea surface condition, and polarization.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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UHF						
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